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THESIS

A PILOT EVALUATION OF

MOVABLE AND RIGID AIRCRAFT CONTROLS

by

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A Pilot Evaluation of
Movable and Rigid Aircraft Controls

by

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ABSTRACT

A simulator facility employing a two-axis compensatory tracking task with a random-appearing signal was used to evaluate the performance of fifty-five pilot and non-pilot test subjects using four separate control sticks -- two movable and two rigid. Pilot acceptance of the rigid cockpit controllers was determined by comparing individual pilot ratings of the sticks. In general, in both performance and opinion, the rigid systems were found to be superior to their movable counterparts. Steps were taken to avoid errors due to pilot bias, learning, adaptation, or fatigue. The results obtained are subject to several test limitations, including the low stick-force levels used, the neglect of aircraft vibration effects, and the realism of the simulation.

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ACKNOWLEDGEMENTS

The Author wishes to express his appreciation to: Professor Donald Layton for his invaluable assistance and guidance throughout the entire program; to the flying and non-flying students of the U. S. Naval Postgraduate School who served so admirably as test subjects; to Commander David W. Caswell, whose thesis laid the groundwork for this investigation; to Commander William Townsend, who assisted in the early phase of the testing program; and to Lieutenant (jg) Vernon Gordon, who assisted the author in the related human transfer function study.

I. INTRODUCTION

With the evolution of modern-day high-performance aircraft, more reliable and responsive flight control systems will be required. As the simple mechanical control systems of the past are replaced by complex linkages and fully-powered and power-boost controls, numerous problems concerned with flight control weight, nonlinearities, friction, hysteresis, inertia, and backlash arise. These problems, together with reliance on stability augmentation systems to assist the pilot in portions of the flight envelope, have stimulated investigations of fly-by-wire techniques (electronic control systems). Fly-by-wire research has now advanced to the stage where test flights demonstrating reliability are being made and are reporting favorable results (Ref. 2).

With a basic change from mechanical to electrical control systems, various possibilities exist for a cockpit controller different from the conventional deck-mounted movable stick. Numerous manipulators have been studied, the most prominent of which is a side-located, limited-motion hand controller (Refs. 3, 4, 5, 6, 7). These systems allow increased cockpit space for flight displays or for additional control functions and depend, for the most part, on a reliable fly-by-wire capability.

The most important considerations, when experimenting with control sticks, are the aircraft handling qualities. The pilot regards stick feel as a particularly valuable cue in maneuvering the vehicle (Ref. 8). With the irreversibility of power-assisted electronic flight control

systems, this feel must be provided artificially to the stick -- whether centered or side-located. Since the pilot relies heavily on this stick force, the actual motion of the controls is of much less importance. In fact it is widely recognized that a pilot seldom, if ever, knows what position his control stick is in (Refs. 5, 9). This suggests a force-only or rigid controller could be applicable to a fly-by-wire control system. A rigid stick might prove more satisfactory, if not for primary control, for a back-up precision tracker to be used for formation flying, terrain avoidance, gunnery runs, weapon control, carrier landings, or ground control approaches. Limited work has been done with rigid sticks (Refs. 5, 10, 11, 12, 13, 14, 15), and the results have been contradictory and essentially inconclusive.

Since handling qualities are inevitably determined from pilot opinion, a simulator facility was developed by Commander D. W. Caswell (Ref. 1) to evaluate pilot acceptance of a rigid cockpit control system and test their ability using it. The simulator employs a two-axis, compensatory tracking task with a repeatable random-appearing signal. This investigation used this simulator to measure pilot performance for fifty-five test subjects on each of four control sticks -- two movable and two rigid. This performance was compared with individual pilot ratings of the separate controllers. Personal pilot experience data were collected to insure a thorough test subject analysis. Scores were also recorded during a portion of the test runs to determine the effect on the data, if any, of pilot learning, adaptation, or fatigue. An approximate

human transfer study was conducted using two sticks and two subjects for the purposes of correlation. Additional qualitative comments from the subjects were recorded and a statistical score-to-rating correlation study was made.

II. THE SIMULATOR FACILITY

The simulator (shown in Fig. 1) for pilot evaluation of the rigid and movable control sticks presents a two-dimensional tracking problem to the test subject. An Ampex tape recorder provides a repeatable test signal which is displayed on an X-Y cathode ray oscilloscope with a five-inch grid. The "instrument panel" is shown in Fig. 2. The pilot-operated control stick generates a signal which, when amplified, acts to cancel out the random input signal from the tape -- moving a pip to the center of the grid. This is accomplished with a summing amplifier. The control stick signal is altered by an analog computer circuit to simulate actual aircraft dynamics. Thus, in his efforts to center the pip on the oscilloscope screen, the test subject has a constant display of his error on the grid. A Brush recorder display of the test signal and a typical pilot's error function in the lateral mode is shown in Fig. 3.

A. THE CONTROL STICKS

Four separate controllers were used in the test program: a movable and rigid deck-mounted (centered) stick, and a movable and rigid side-located manipulator. The movable sticks employed variable potentiometers for signal generation, while the rigid sticks used strain gages in a Wheatstone bridge circuit. A light stick force was provided in the movable controllers by artificial-feel springs, although in the movable side-arm system the spring force was inadequate to center the stick.

Thus, the side-located controller was essentially free-moving or unrestrained.

In the rigid sticks, allowing negligible deflections, the control force bending moments activated the strain gages providing the control signal. The rigid controllers were constructed identical in size to their movable counterparts, and their force levels were very low to provide a similar control action for each stick.

All the sticks were wired to a sixteen-connector plug for a quick-change capability. The control signals were amplified by a factor of two hundred for the rigid and one for the movable systems before their input to the analog computer dynamics circuits.

B. COMPUTER CONTROL DYNAMICS

The lateral and longitudinal control signals were changed by the analog computer circuits to simulate the response of an aircraft. The longitudinal circuit provides a damped short-period oscillation approximating the dynamics of the F-4 aircraft at a Mach number of 0.9 at sea level. The computer response to a step input in pitch is shown in Fig. 4. The lateral circuit provides a damped first-order response simulating a stable aircraft. A step input in yaw gives the response shown in Fig. 5.

C. THE TEST SIGNAL

The random input signal from the tape deck consisted of eight segments:

1) Two minutes zero signal (pip centered)

2) One minute longitudinal signal only

3) Thirty seconds zero signal

4) One minute lateral signal only

5) Thirty seconds zero signal

6) One minute combined longitudinal and lateral signal

7) Thirty seconds zero signal

8) Three minutes combined signal (scoring run).

A Brush recording of the entire scoring run showing the signal magnitudes in both the lateral and longitudinal channels is shown in Fig. 6.

D. THE SCORING MECHANISM

The scoring of a test subject is based on the time duration (in seconds) of errors which drop below a pre-set level, i.e., the amount of time the pip is in a small scoring circle in the center of the oscilloscope grid. When the error exceeds the specified amount (when the pip leaves the circle), a signal comparator stops the oscillator signal which runs the timer. A green indicator light on the instrument panel also goes out, telling the pilot he is out of the scoring circle. The panel also contains a blue indicator light to signal when the scoring run is in progress.

A complete list of equipment used is given in Appendix A. Further, more detailed information concerning the simulator facility may be found in Ref. 1.

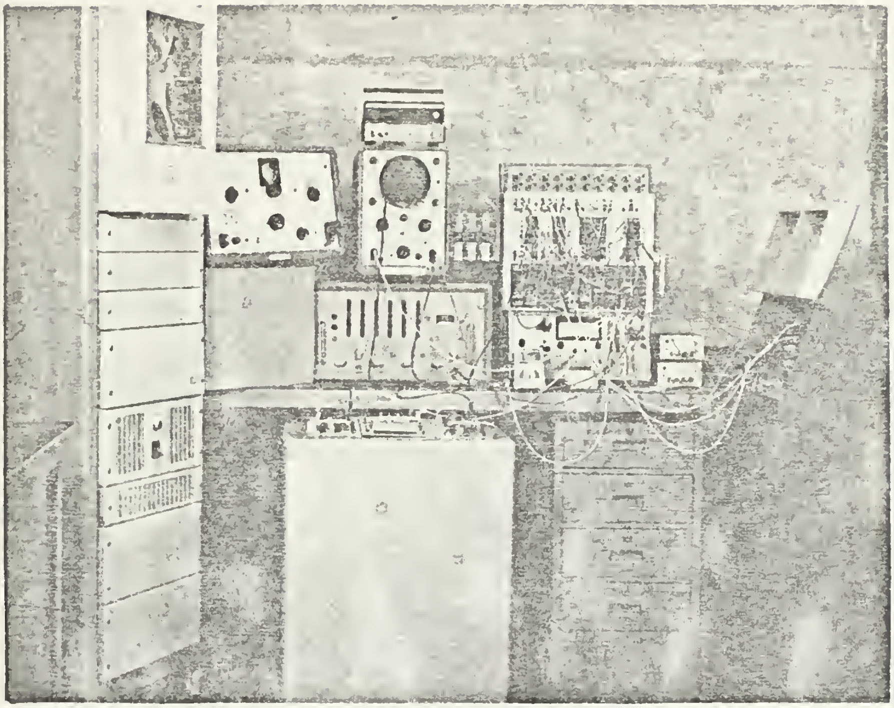

Figure 1.   The Simulator Facility

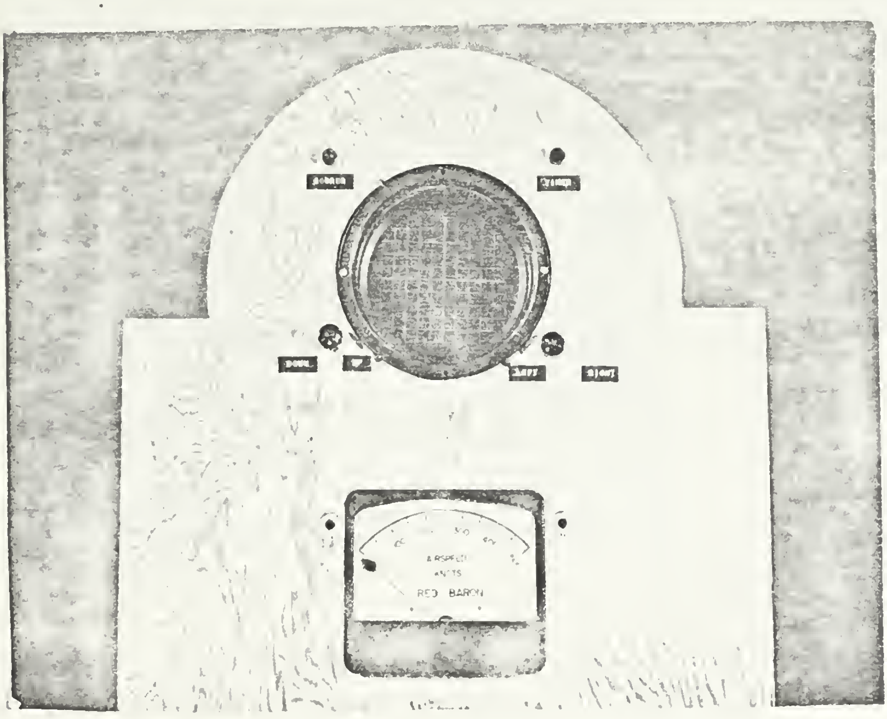

Figure 2.   The Cockpit Instrument Panel

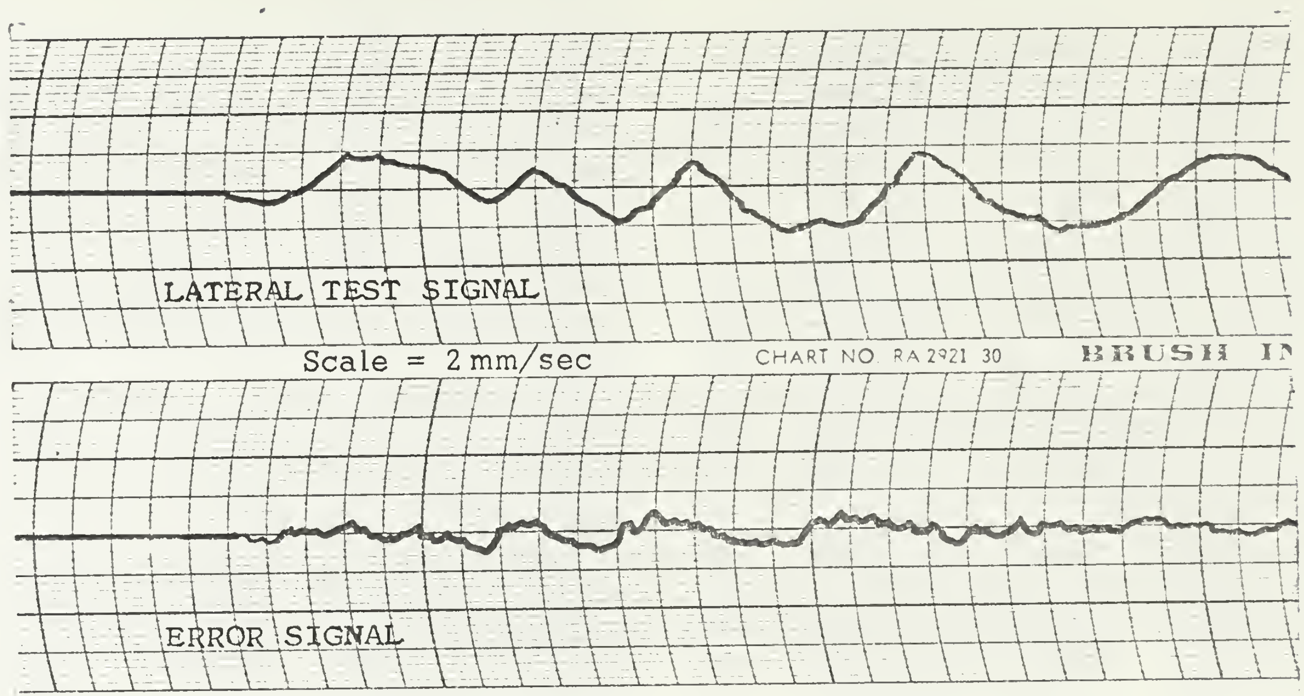

Figure 3. Typical Pilot Tracking Error

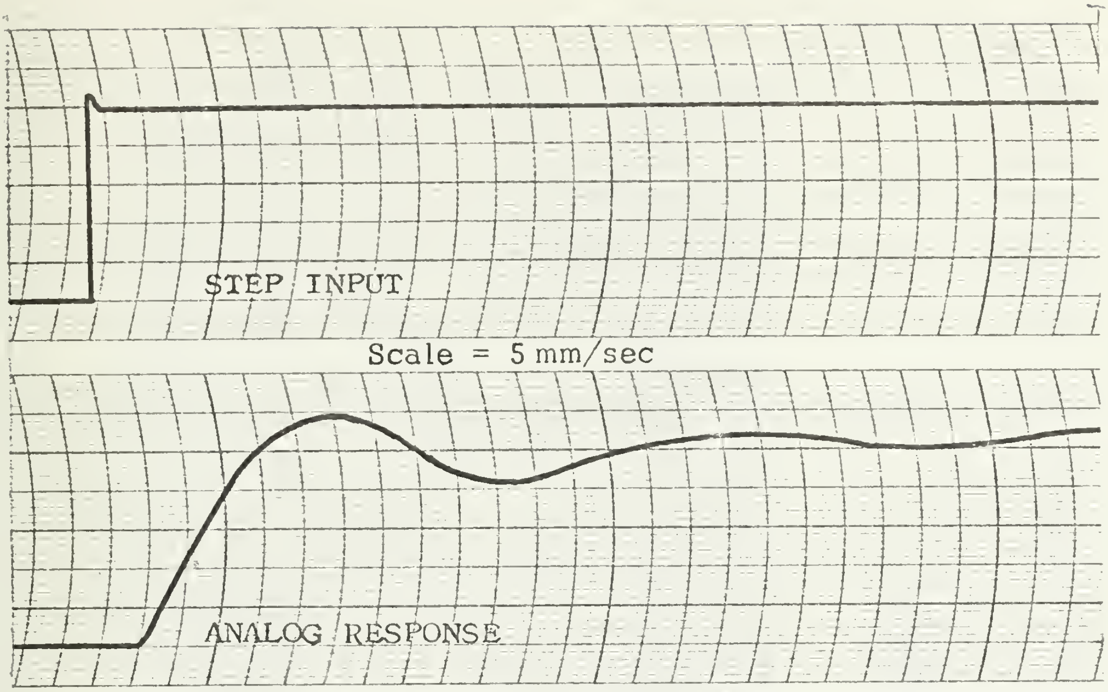

Figure 4. Longitudinal Response to Step Input

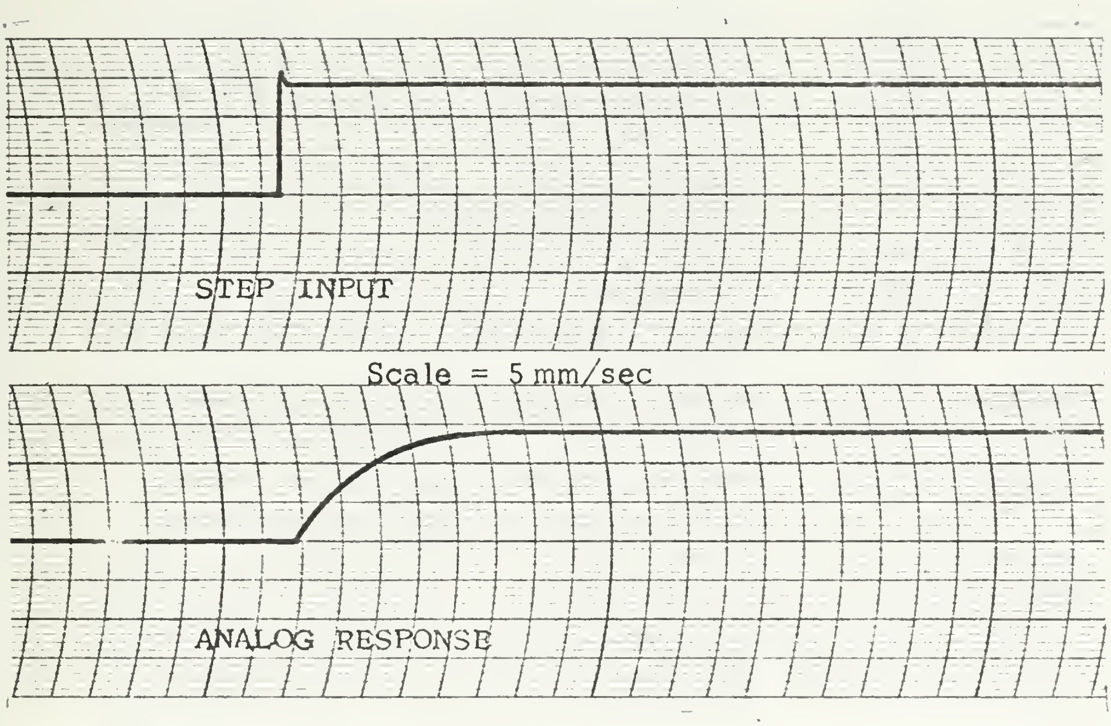

Figure 5. Lateral Response to Step Input

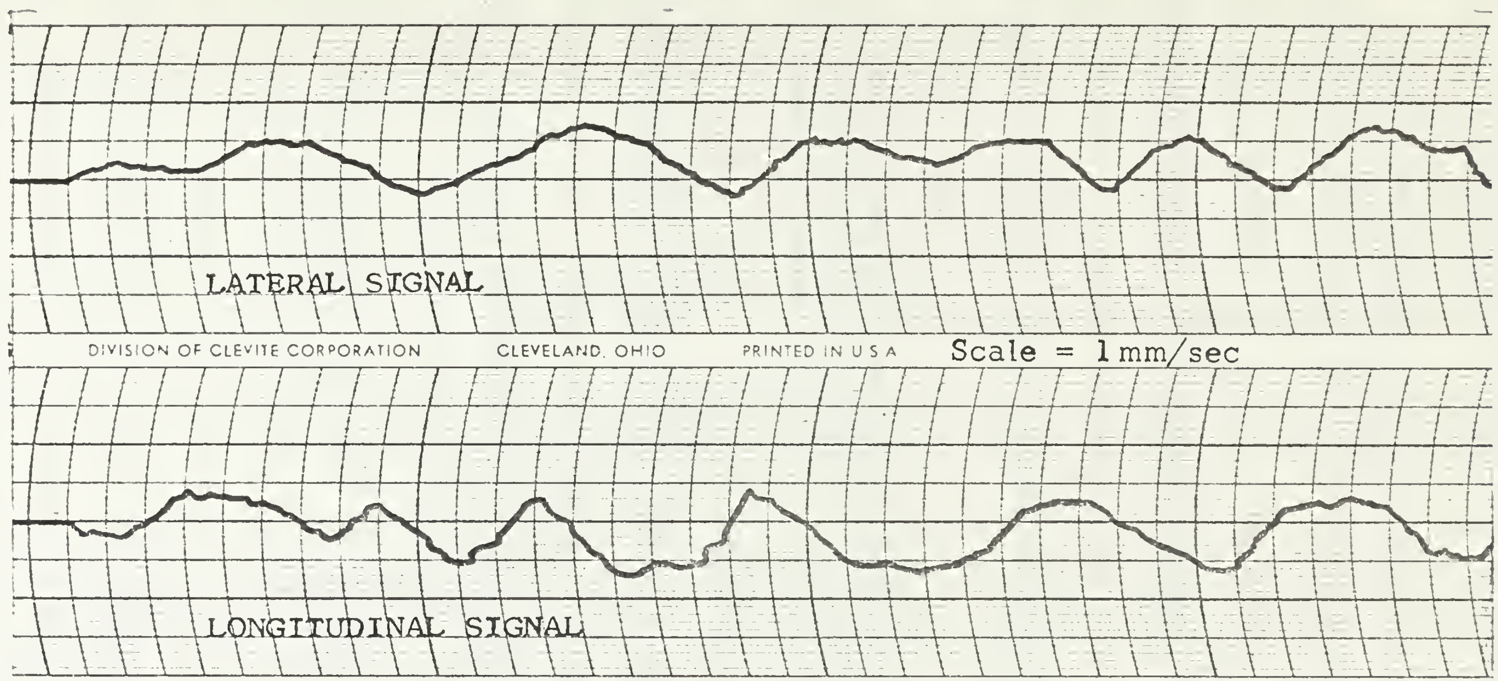

Figure 6. Scoring Run Input Signals

III. PROCEDURES FOR TESTING AND PILOT EVALUATION

Before the beginning of each test run, the subjects were briefed on the operation of the simulator and the testing plan. Explanations were given regarding the nature of the various control sticks, the size of the scoring circle, and the control motion and force to give a desired pip deflection. Also the meaning of the blue and green indicator lights, the tape input signal order, the testing order of the sticks, and the length of the run were given.

The test was initiated by selecting the proper stick switch on the patch panel and turning on the tape. The first two-minute segment of the tape input -- the zero signal -- was used to balance the potentiometers (centering the scoring circle on the grid) and to allow the pilot to center the pip. The subject then used the one minute of longitudinal signal, one minute of lateral signal, and one minute of the combined two-axis signal with which to practice and to become adapted to the particular control stick. The final three-minute segment of the input signal, the two-degree-of-freedom motion, was used for the scoring run. The pilot was informed when the test signal changed modes and was allowed thirty-second rest periods between the various segments of the tape. Adequate warning was given prior to the beginning of the scoring run, and the subject was also notified when one minute remained in the test. At the end of the run, the tape was rewound, a changeover switch

was made to another stick, and the testing process repeated using the identical input signal.

At the end of the test, the subjects were asked to complete a questionnaire evaluating the control sticks and providing precise information concerning their total flight experience. These evaluations were made before the pilots were told their scores on each stick. The questionnaire used is shown in Table I.

For an adequate pilot evaluation of the controllers, a rating scale was required. In the past, handling-qualities research has usually employed the standardized Cooper rating scale (Ref. 16) or, more recently, the modified Cooper-Harper scale (Ref. 17). Caswell's preliminary testing (Ref. 1) used the original Cooper scale and several of his testees gave two different sticks an identical rating. In an effort to avoid this situation, a new rating scale was devised to allow for a finer discrimination in the evaluation of the four control sticks. This scale allows a wider range of "satisfactory" ratings, while still providing the opportunity for giving an adverse opinion. The revised rating scale is given in Table II.

Caswell's testing also found a tendency for the test subjects' performance to improve as the test progressed from one stick to another. For this reason the testing order was varied to cancel out the effects of a possible learning function. Since the primary purpose of this study was to compare rigid with movable controls rather than center with side-located sticks, the variation of test order was concerned only with

alternating the movable versus the rigid systems. Thus in each system the deck-mounted center stick was used first.

To determine any possible learning, fatigue, or adaptation during the course of one run, partial scores were observed and recorded at thirty-second intervals for thirteen test subjects. Finally, qualitative comments by the pilots concerning the validity of the simulation and the applicability of a rigid cockpit control system were recorded.

TABLE I

PILOT QUESTIONNAIRE

Name ____________________ Test Number ______________

Age ______ Date ____________________

FLIGHT EXPERIENCE

Approximate Number of Pilot Hours in:

Single-Engine Jet	________
Multi-Engine Jet	________
Single-Engine Prop	________
Multi-Engine Prop	________
Helicopter	________
Light General A/C	________
Non-Pilot	________

Type of Operational A/C with Most Experience (F-4, A-4, etc.)? ______

Type of Operational A/C with Most Recent Experience? ______

How Long Since Piloted Any Aircraft? (If over one month) ______

How Long Since on Full-Time Operational Flight Status? ______

PILOT OPINION AND PERFORMANCE

	Pilot Rating	Test Score	Preference
Movable Center Stick	________	________	________
Movable Side-Arm Stick	________	________	________
Rigid Center Stick	________	________	________
Rigid Side-Arm Stick	________	________	________

TABLE II

PILOT RATING SCALE

Numerical Rating -- Descriptive Phrases

1 - Fantastic, could not be improved, should be in all aircraft.

2 - Excellent control response, no gripes.

3 - Good response, pleasant to fly.

4 - Good response, but would require some getting used to.

5 - Satisfactory operational response, would expect no difficulty.

6 - Satisfactory, would expect minor problems in certain situations.

7 - Acceptable, but with some unpleasant characteristics.

8 - Unacceptable for normal operations.

9 - Unacceptable for any operations.

10 - Unsatisfactory, dangerous, uncontrollable.

IV. ANALYSIS AND CLASSIFICATION OF TEST SUBJECTS

To properly interpret the data in a test of this sort, it is necessary to have background information on the test subjects. The extensive flight experience data obtained from the pilot questionnaire is given in Appendix B.

Included in the fifty-five subjects tested were Naval aviators, Naval Flight Officers, private pilots, and non-pilots representing a broad spectrum of aircraft flight experience. The private and non-pilots tested can be considered as representative of the type of personnel who enter Naval flight training.

A. PILOT CLASSIFICATION

To facilitate an interesting and meaningful evaluation of the scores and ratings, the testees were classified into five major groups:

1) Jet pilots 18
2) Propeller (prop) pilots 14
3) Helicopter (helo) pilots... 9
4) Private (pri) pilots 8
5) Non-pilots............... 9

It is seen that a relatively even distribution was obtained -- there are enough subjects in each category to insure an accurate data base. Three pilots (Numbers 5, 12, and 29) had significant experience in two different categories and thus were included in both. The classification of each pilot is also included in Appendix B.

This division was felt necessary for several reasons. First, it was thought necessary to evaluate the opinions and performance of the pilots in light of their experience. Different types of pilots use different control sticks. In general, the jet and helicopter pilots are experienced with the conventional, deck-mounted movable stick, while propeller and private pilots use a yoke or wheel controller. Single engine propeller aircraft do have the movable center stick, however only two pilots had the majority of their experience with this type (flight instructors). Second, pilot classification of the data could give an indication of the type of aircraft in which a rigid stick might be more applicable. For example, if jet pilots should find a particular preference for the rigid control stick, this system might be of use in jet aircraft. Finally, the performance and evaluation by non-pilots compared with those of pilots is necessary to determine the effect of long-established flying tradition on the opinions of the pilots. It must be mentioned, however, that the non-pilot group tested did have a limited amount of flight experience, although in most cases it was less than twenty hours.

B. TEST SUBJECT ANALYSIS

The age of the average subject tested was 27.9 years, with thirty-seven of the testees between 27 and 32 years of age. A significant age difference of 5 to 12 years was noted between the non-pilots and pilots.

Thirty-seven of the forty-six pilots had flown some type of aircraft within one month of the day they were tested (proficiency flying). The average time since any flight was 2.77 months, including only five subjects who had gone over a year without flying. In general, the private pilots had not flown recently.

The thirty-eight Navy and Marine pilots tested were students and not on operational flight status. The average time since they had been flying operationally was 13 months. Twenty-seven pilots had been on operational status between 5 and 12 months prior to their test. Only five of the Navy pilots had not been on flight status in more than $2\frac{1}{2}$ years.

The airplanes in which the thirty-eight military pilots had the most experience present a wide variety of Naval aircraft. These are:

JET:	A-4, A-6, A-7, F-4, F-8
PROP:	A-1, P-5, P-2, P-3, S-2, T-28, C-121
HELO:	H-2, H-4, H-34, SH-3

Twenty-nine of the Navy and Marine pilots had their <u>most recent</u> experience in the same aircraft in which they had the <u>most</u> experience. Only one pilot had his most recent experience in an airplane of a different type (a helo pilot in an S-2).

The average military pilot tested had flown 2200 hours total flight time, with thirty-three out of thirty-eight pilots between 1000 and 4000 hours. The private pilots had significantly less flight experience, with an average of 200 hours apiece.

Thus in general it can be seen that the subjects tested were moderately experienced military pilots, about 30 years of age, who had been on operational flight status one year ago and were making proficiency flights in their aircraft type at the time of their test in the simulator.

V. TEST RESULTS

By the end of the testing program, results were obtained from fifty-five subjects, including nine non-pilots. The data obtained -- test scores, pilot ratings, and testing order -- are given in Appendix C. Several methods of data reduction and comparison were utilized for a complete and meaningful evaluation of the test results. Average scores and ratings were computed for each pilot classification and for the entire test group. Since averages can give an incomplete view, the raw scoring and pilot rating distributions are given to supplement the averaged performances and opinions. In addition to the comparison of the various control sticks, the individual pilot classifications are compared to further illuminate the subject.

A. AVERAGES

The over-all average test score for each stick, out of a possible total of 180 seconds, is given in Fig. 7. It is evident that the body of test subjects did better with the rigid controllers than with the movable sticks. The best performance was on the rigid side-arm stick, while the poorest by far was with the movable hand controller. The average score with the movable center stick, while lower, compared favorably with the rigid systems.

Figure 8 presents the average pilot rating for each stick. The rigid sticks were preferred overwhelmingly over the movable controls.

The force-only sticks were found to have "good response," while the movable controllers were rated only "satisfactory." The subjects tended to dislike the movable side-arm stick, and little difference was noted between the two rigid manipulators. At least on the average, pilot opinion correlated with actual performance. A more detailed score-to-rating correlation study is included in Section VI.

B. COMPARISON OF STICKS

More detailed comparisons of the four control sticks for a particular pilot class are shown in Figs. 9 and 10. These results (Fig. 9) show that all groups do better with the rigid controls to varying degrees. We also see that jet, helicopter, and non-pilots exhibit performance variations identical to those of the over-all averages (Fig. 7); i.e., rigid side-arm -- best and movable side-arm -- worst. Notable differences are : 1) the prop pilots do slightly better with the rigid center stick than with the rigid hand controller, rather than vice versa, and 2) private pilots scored higher with the movable side stick than with the movable deck-mounted stick.

It is evident from Fig. 10 that all pilot groups preferred the rigid to the movable controls and disliked the movable side stick. Opinion was fairly evenly divided as to which stick was the best -- rigid center or rigid side-arm. The relative magnitudes of all the rating averages are about the same, indicating the pilots' interpretations of the rating scale were quite uniform.

C. COMPARISON OF PILOT CLASSES

Actual comparison of the different pilot groups for a particular control stick are given in Figs. 11 and 12. This analysis reveals that private pilots and non-pilots scored higher than pilots with the rigid control sticks. As expected, jet pilots performed superior to the other groups using the conventional movable center stick. The results also indicate prop pilots encounter difficulty with the side sticks, and both prop and helo pilots score generally below average on all sticks.

D. SCORE AND RATING DISTRIBUTION

To contribute to the averaging analysis, charts of the test score and pilot rating distributions were made. The over-all performance distribution plot of Fig. 13 gives the percentage of the total number of test subjects whose final score on a particular stick was in each 5-second time interval throughout the range of test scores. A statistical distribution of scores about the average is approached with the two rigid sticks and the movable center stick (Fig. 13a, b, c). However, the movable side-arm stick is marked by a rather even distribution of scores concentrated at the lower end of the scale.

The over-all pilot opinions (Fig. 14) are somewhat more divided on the movable sticks than on the rigid systems -- especially in the case of the movable hand controller, where the ratings are particularly scattered.

Identical performance and pilot opinion distribution charts for the different pilot groups are included in Appendix D. Facts of interest from

these graphs are: 1) Jet pilot scores on the movable side stick were divided in two groups -- one average and one poor (Fig. D-1d), 2) Two individual prop pilots scored extremely low on the rigid hand stick -- lowering the over-all performance average for the group (Fig. D-3b), and 3) While the scores of private pilots were concentrated, their opinions of all sticks were scattered -- indicating not enough private pilots were tested for a valid comparison (Figs. D-7, D-8).

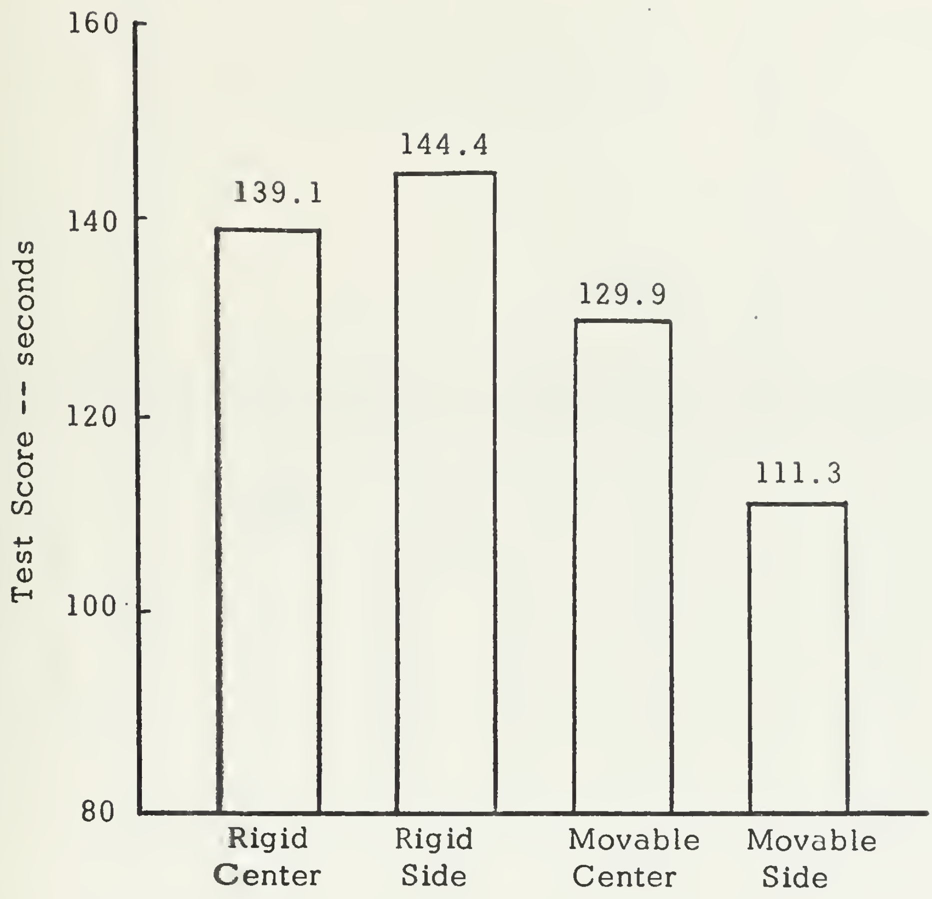

Figure 7. Average Test Score with Each Stick -- All Subjects

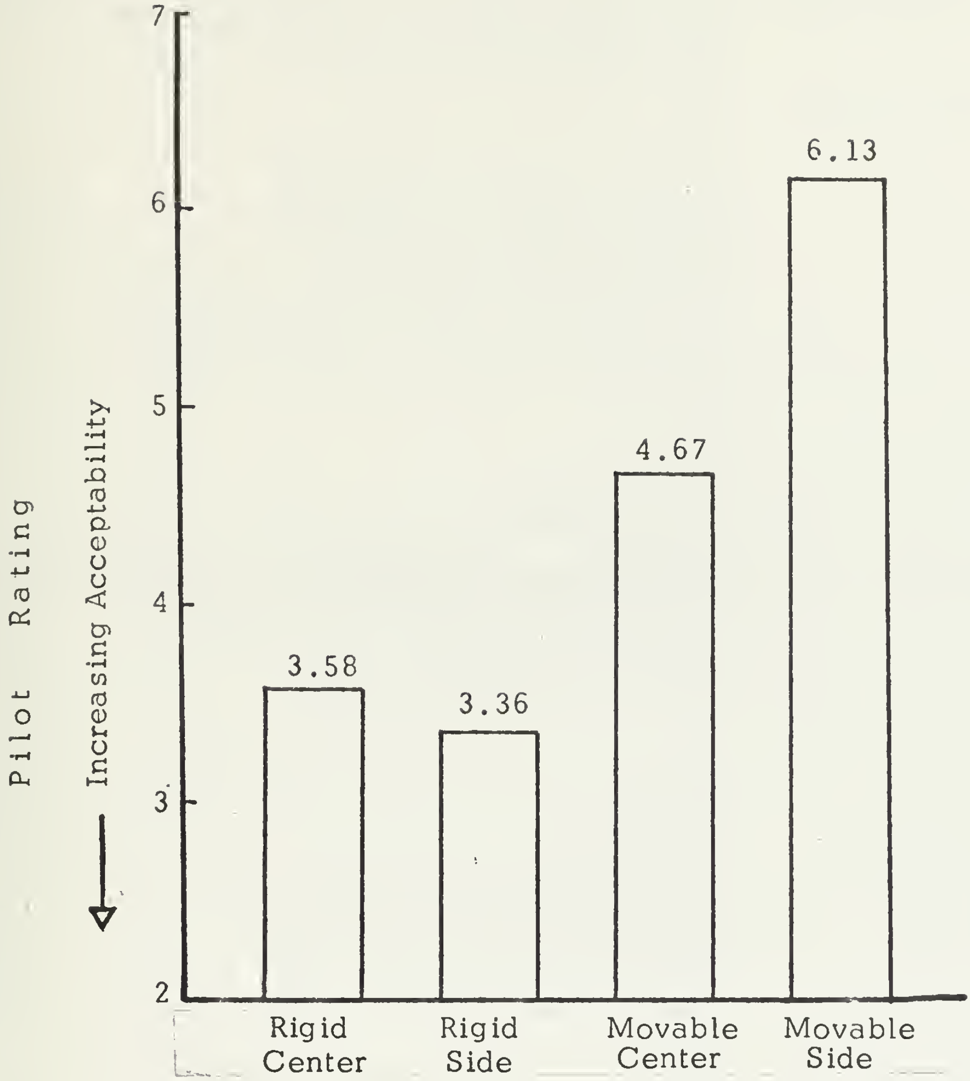

Figure 8. Average Pilot Rating for Each Stick -- All Subjects

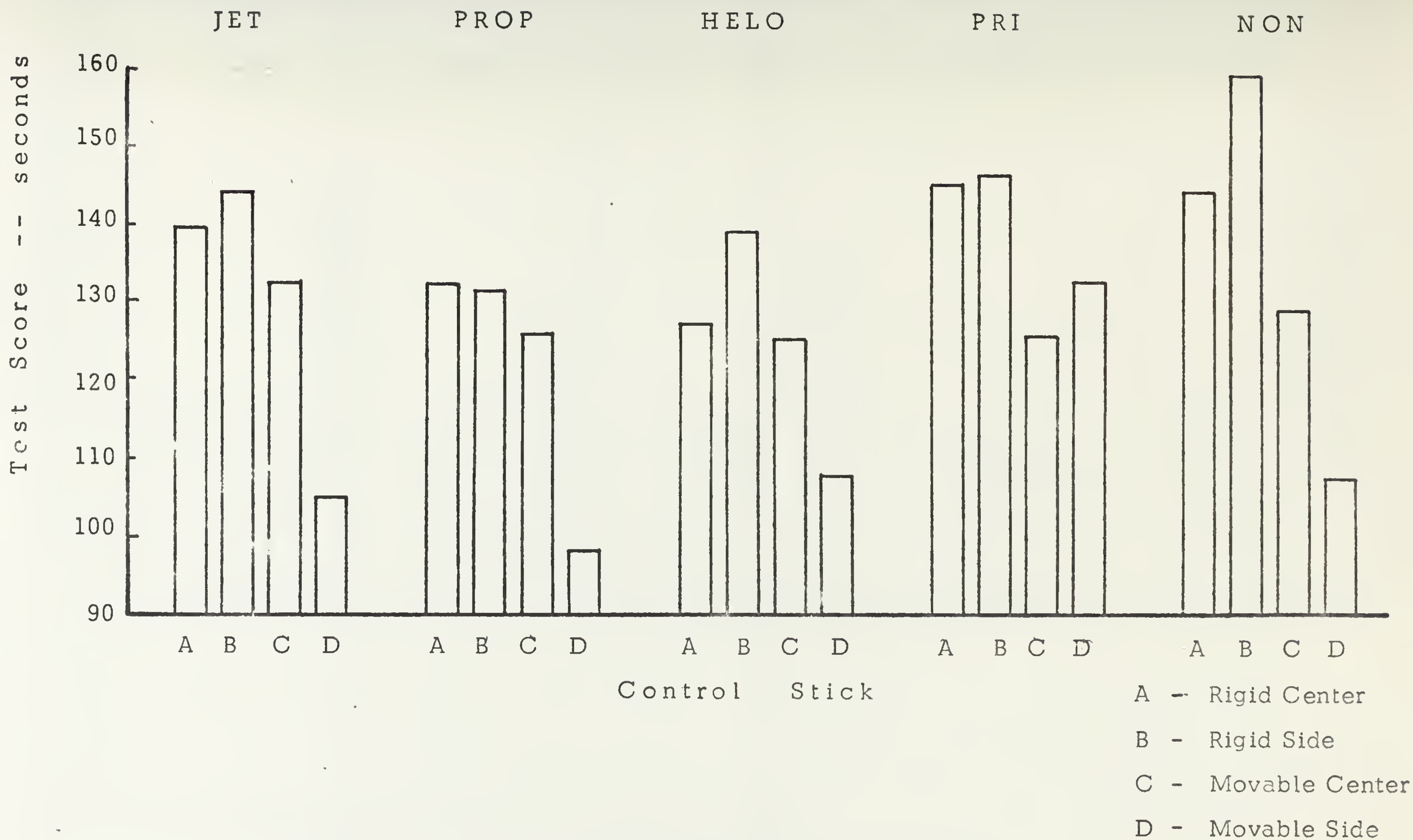

Figure 9. Average Test Score by Each Pilot Classification

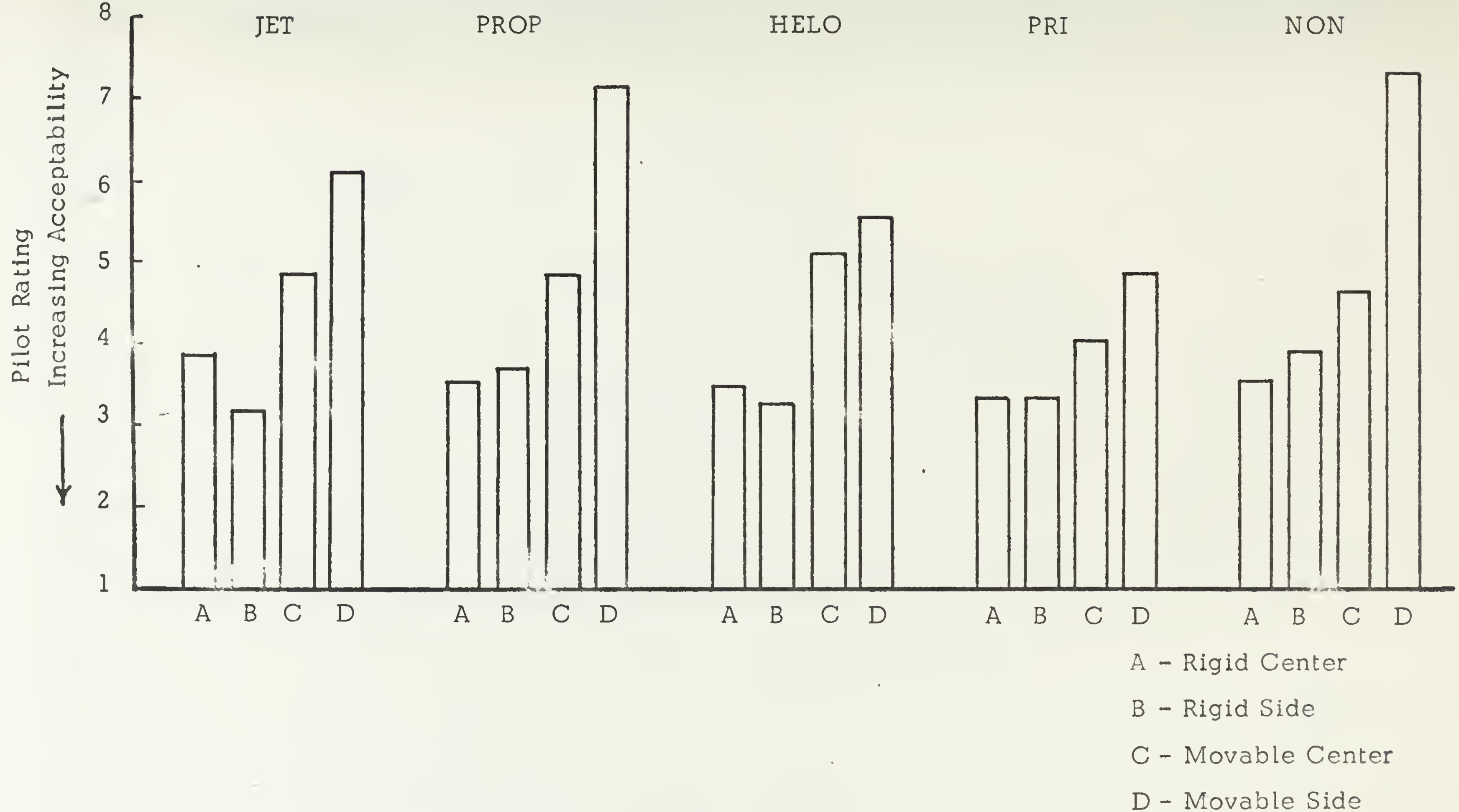

Figure 10. Average Rating By Each Pilot Classification

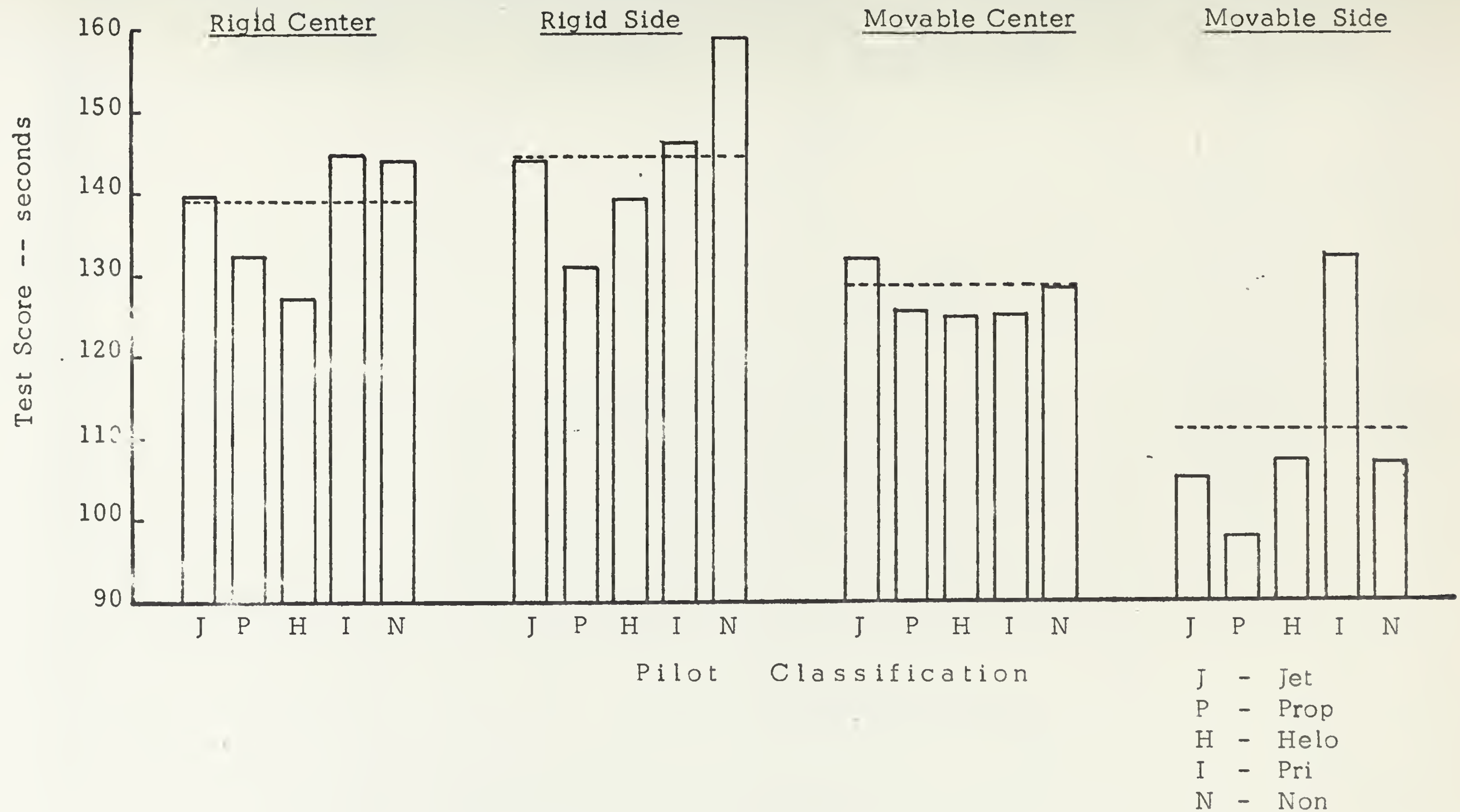

Figure 11. Average Test Score By Pilot Class For Each Stick

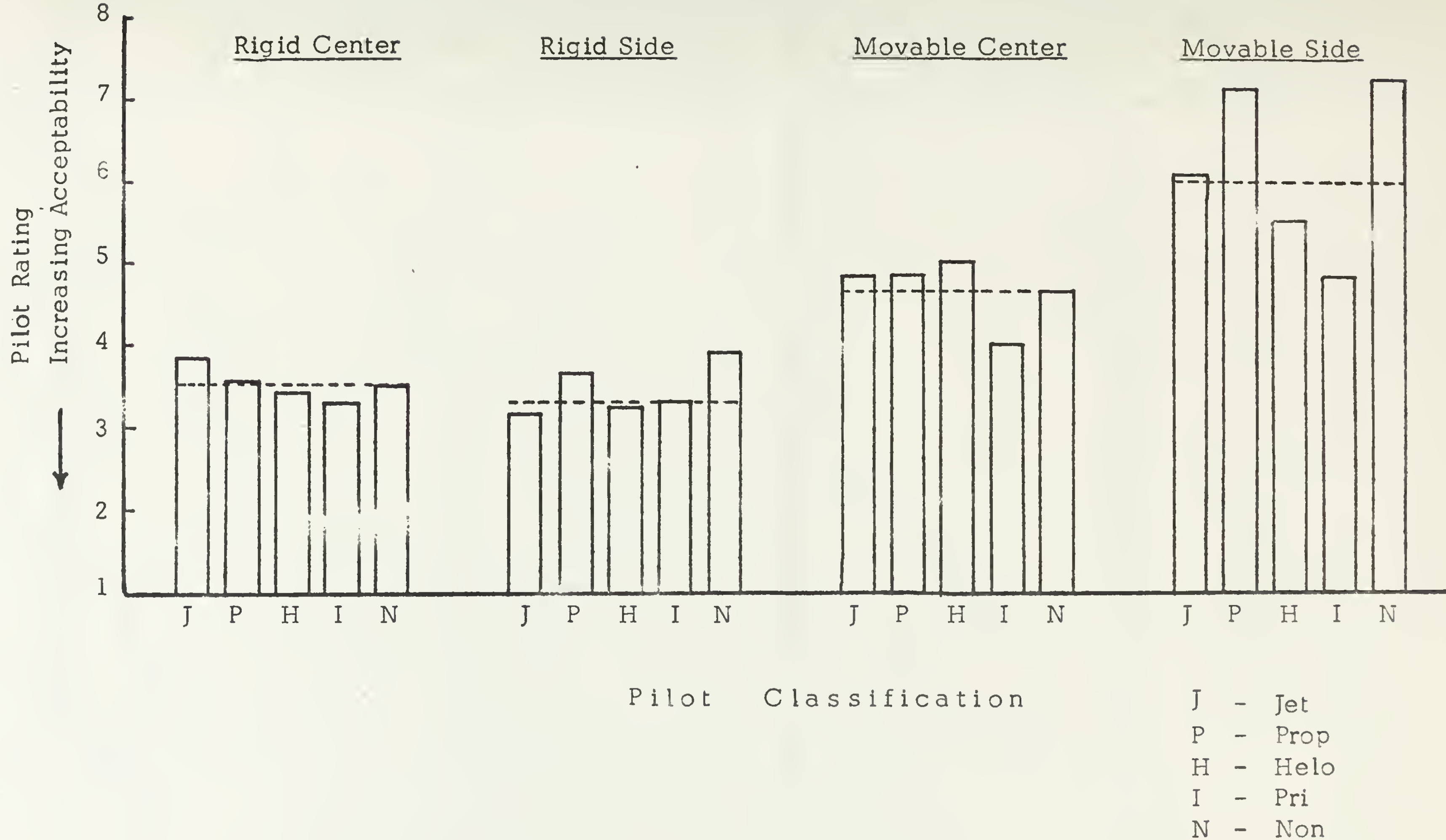

Figure 12. Average Rating By Pilot Class For Each Stick

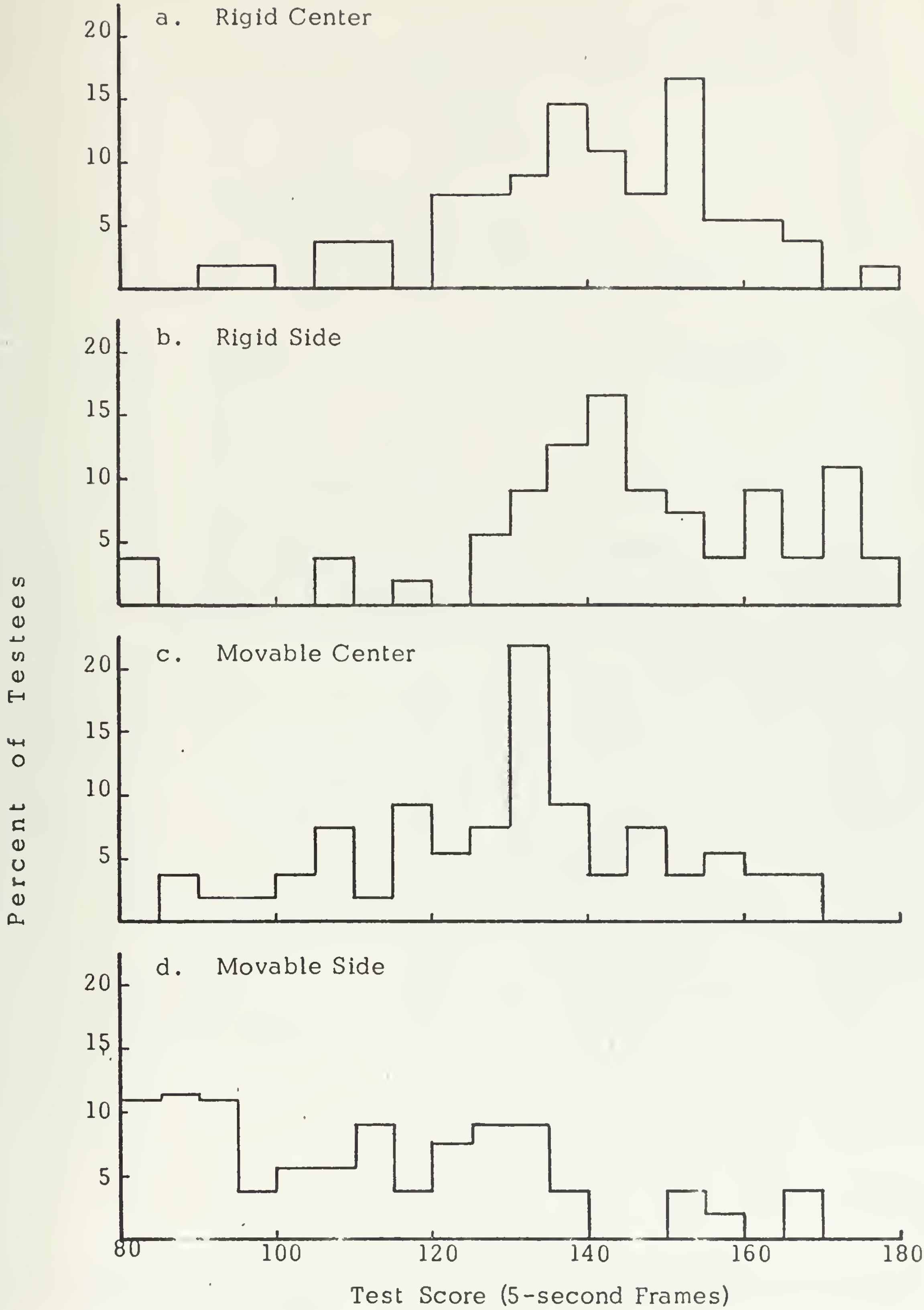

Figure 13. Distribution of Test Scores -- All Subjects

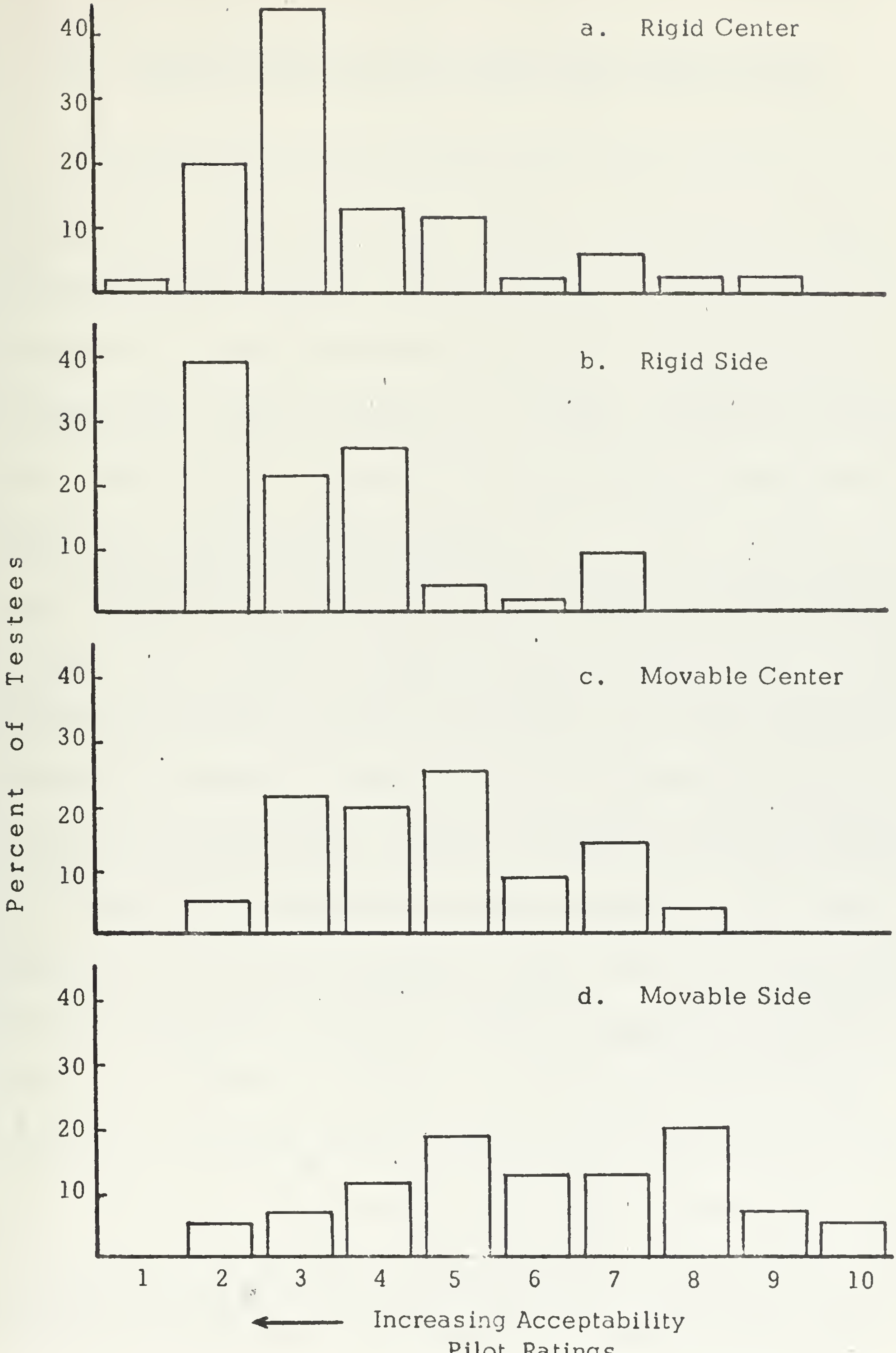

Figure 14. Distribution of Pilot Opinions -- All Subjects

VI. HUMAN FACTORS INVOLVEMENT WITH TEST VALIDITY

In a test program of this nature, dealing with variations in pilot ability and the vagaries of personal opinion, a great deal of care must be taken to insure validity of the data. Human involvement errors can be introduced by myriad differences in adaptation, learning, fatigue, and experience, and by fluctuations in attention, motivation, and judgement. Safeguards must be established and checks need to be made to cancel these possible sources of error.

To determine the nature of human involvement, several methods of analysis were utilized. A score-to-rating correlation study was made to determine the effects, if any, of pilot bias. A standard regression analysis was applied to the data as a means of representing each score and rating on a single graph. Learning, adaptation, and fatigue of the test subjects were explored by observing the variation of performance throughout a run and then throughout the test --the testing order of the four sticks being a key parameter. Additional information concerning learning and adaptation as well as variation in stick dynamics was sought by an approximate human transfer function study with the simulator. A check was also made to find the variation in test results due to a change in the magnitude of the pip deflection, since it could possibly have been altered at some time during the five-month testing program. Finally, the realism or validity of the simulation was studied by comparing

non-pilot performance to that of pilots and by soliciting individual comments from the pilots tested.

A. SCORE-TO-RATING CORRELATION

With the introduction of a different new device like the rigid control stick, the possibility exists that a pilot could become enhanced with its novelty and evaluate it accordingly. On the other hand, a pilot with many hours experience with a movable deck-mounted stick might tend to dislike the rigid controls, even though his performance is superior using them. To determine the magnitude of this type of problem in the testing program, a score-to-opinion correlation analysis was applied. Plotting the over-all average scores versus the average ratings for each stick as shown in Fig. 15 gives a first approximation as to how well the pilot opinions correlate with performance. The strong correlation is obvious, since the rating becomes rapidly less favorable (higher) with a decreasing test score. Similarly, in Fig. 16 a regression analysis plotting score versus rating and reducing the points to a single line for each stick shows this strong correlation of performance to pilot evaluation.

For a more detailed analysis, an individual correlation factor "r" was calculated for each pilot. These factors are listed in Table III, with a perfect correlation being r = -1, since the pilot rating decreases as the performance increases. From the table we see that twenty-nine of the subjects have a high correlation of -.8 or better. Fourteen (25%) of

of the subjects tested have a poor score-to-rating correlation (above -.4). A close examination of the scores and ratings of these fourteen testees reveals the causes of the poor correlations. Eight of these subjects -- Numbers 13, 22, 35, 39, 40, 43, 50, and 52 -- were excluded from the correlation analysis, because their poor correlations were due to nearly identical scores on separate sticks or to identical ratings to more than one stick. The remaining six poor correlations were possibly influenced by pilot bias. Four of these subjects preferred the movable controls but scored higher with the rigid systems. The remaining two subjects scored well with the movable sticks but preferred the rigid controls.

The average correlations for each pilot class are of interest and are given in Fig. 17. As expected, the less-experienced private and non-pilots had significantly lower score-to-rating correlations than those of the military pilots.

Thus, with a high over-all average correlation of -.68, it appears that pilot bias had little effect on the data. The majority of the subjects had relatively high performance-to-opinion correlations. The poor correlations were small in number, and the errors induced tended to cancel one another.

B. LEARNING, ADAPTATION, AND FATIGUE

In the preliminary testing by Commander Caswell (Ref. 1), the pilots' skill with the simulator tended to improve as the test progressed.

To avoid allowing one type of stick to obtain an advantage over the other, the testing order (movable vs. rigid) was changed for each subject. Thirty subjects used the rigid controls first, and the remaining twenty-five started with the movable sticks. Thus any possible learning function effects should have been nearly eliminated. Evaluating the increase in score from the first stick used to the next, the average learning was of the order of one second and thus essentially negligible.

An almost universal comment from the pilots upon finishing the test was that the tracking task was extremely tiring. To further reveal learning, adaptive, or fatigue factors, partial scores were recorded at 30-second intervals throughout the three-minute test run for fourteen test subjects. The results obtained are displayed in Fig. 18. It is evident that test scores dropped off rather rapidly in the final 30-second frame. This could be due to fatigue or possibly due to the fact that the pilots were given a notification one minute before the end of a run. Motivation may have lowered slightly in anticipation of the end of a somewhat tedious test.

Little evidence of slow adaptation to the sticks can be found on the graph. The subjects in general appear to have become fully adapted to each controller during the practice time preceding the scoring run. The scores in the first frames show only a slight improvement in performance, with actually a decrease using the movable side-arm stick. This is not surprising since human operator control adaptation usually occurs in 1-3 seconds following a change in simple tracking conditions (Ref. 18).

An effort was made to compute an approximate human transfer function for two test subjects using the simulator facility. It was hoped a further more analytical description of human adaptation and learning could be found (Ref. 19). The subjects completed a sinusoidal tracking task in the lateral mode at various frequencies of oscillation, using the movable center stick and the rigid side-arm controller. Their frequency response was recorded and is illustrated in the Bode plots of Figs. 19 and 20. Pilot transfer functions were obtained from these plots by the asymptotic approximation method. The similar form of the curves indicates that human response, and thus adaptation, is comparable for a given stick; but the response to two different sticks can be quite diverse. It was not attempted to apply these results to the data since the study was approximate, and indication of adaptive difficulty in the tests was absent.

C. SCORING PIP DEFLECTION

Since the testing program was extended over a several-month period, the motion of the pip on the oscilloscope for a given control force could quite possibly have been changed. This could have occurred due to other use of the Ampex tape recorder or actual tape deterioration. To check this source of error, three subjects were tested at two different pip deflections -- one large and one small. As might be expected, the scores with a small deflection were much higher as the pip was easier to control. However, little change was found in the relative differences

among the four control sticks. Thus it was assumed that even if slight changes occurred in the pip deflection, the error, for stick comparison purposes, was minimal.

D. TEST LIMITATIONS AND SIMULATION VALIDITY

Most pilots seemed to agree that while their scores and ratings were higher using the rigid systems in the simulator, the situation might be significantly different in an actual aircraft. Herein lies the major limitation to a simulated opinion survey of this sort. It was felt by the pilots that actual flight testing is necessary to determine, for sure, pilot acceptance or rejection of a rigid control stick. The relatively high scores of the non-pilot group cast further doubt on the realism of the simulation; the age differential between pilots and non-pilots could be a factor, however.

Another key limitation concerns the low force gradients incorporated into all four sticks. The maximum force necessary was about one pound, while the optimum stick force per g in an actual aircraft is 5-7 pounds (Ref. 20). A more thorough and comprehensive study would include the effects of variations of stick force per pip deflection on pilot opinion and performance. Of particular note in this investigation was the essentially free-moving, unrestrained motion of the movable side-arm controller. Quite possibly a spring-restrained movable hand stick would fare much better in comparison with the rigid systems. On the other hand, higher force levels in the rigid sticks might make them even more acceptable.

This survey is further limited in that the relative effects of vibration using the control sticks were ignored. Aircraft vibration can reduce the manual dexterity of the pilot and introduce an additional unsteadiness in his control motion. The human body tends to damp out vibration; thus problems could arise with side-stick controllers where the pilot's arm rests on a surface vibrating with the airplane. Reference 2 reported that a movable control stick gave performance superior to the rigid controller at all exciting frequencies of vibration tested. Vibration would naturally enter a flight testing program and could also be introduced into a simulator. The effects of acceleration on control stick performance must also be studied in a flight test rather than a simulator investigation.

During the course of the testing several pilots were concerned about the effect on a rigid controller of conventional stick-mounted trim switches and microphone buttons. While these switches create no stick motion when in operation, they would involve the addition of an extra force on a rigid control stick. This would mean applying an equal and opposite force while using trim tabs to avoid an unwanted control deflection. This problem could be included in a further simulator study.

A final limitation might lie in the fact that the subjects tested were not trained test pilots as is the custom in handling-qualities simulator studies. The limited qualitative nature of information requested in the evaluation of the sticks, however, should have relieved this requirement. The high score-to-rating correlations achieved by the pilots

supports this assumption. In addition, it was desired to determine the opinions of the <u>average</u> fleet pilot with regard to acceptance of a rigid cockpit control system.

TABLE III

INDIVIDUAL PILOT SCORE-TO-RATING CORRELATION FACTORS

Subject	r	Subject	r	Subject	r
1	-.912	20	+.206	38	-.952
2	-.978	21	-.982	39	-.149
3	-.718	22	-.394	40	-.109
4	-.972	23	-.546	41	-.990
5	-.350	24	-.829	42	+.803
6	-.951	25	-.971	43	0.000
7	-.460	26	-.642	44	-.918
8	-.539	27	-.932	45	-.941
9	-.619	28	-.952	46	-.669
10	-.911	29	-.994	47	-.900
11	-.660	30	-.985	48	-.993
12	-.697	31	-.965	49	-.758
13	+.978	32	-.926	50	-.007
14	-.768	33	-.900	51	-.914
15	-.804	34	-.204	52	-.260
16	-.746	35	+.453	53	-.004
17	-.948	36	+.576	54	-.532
18	-.833	37	-.426	55	-.876
19	-.967				

A perfect score-to-rating correlation is r = -1.00.

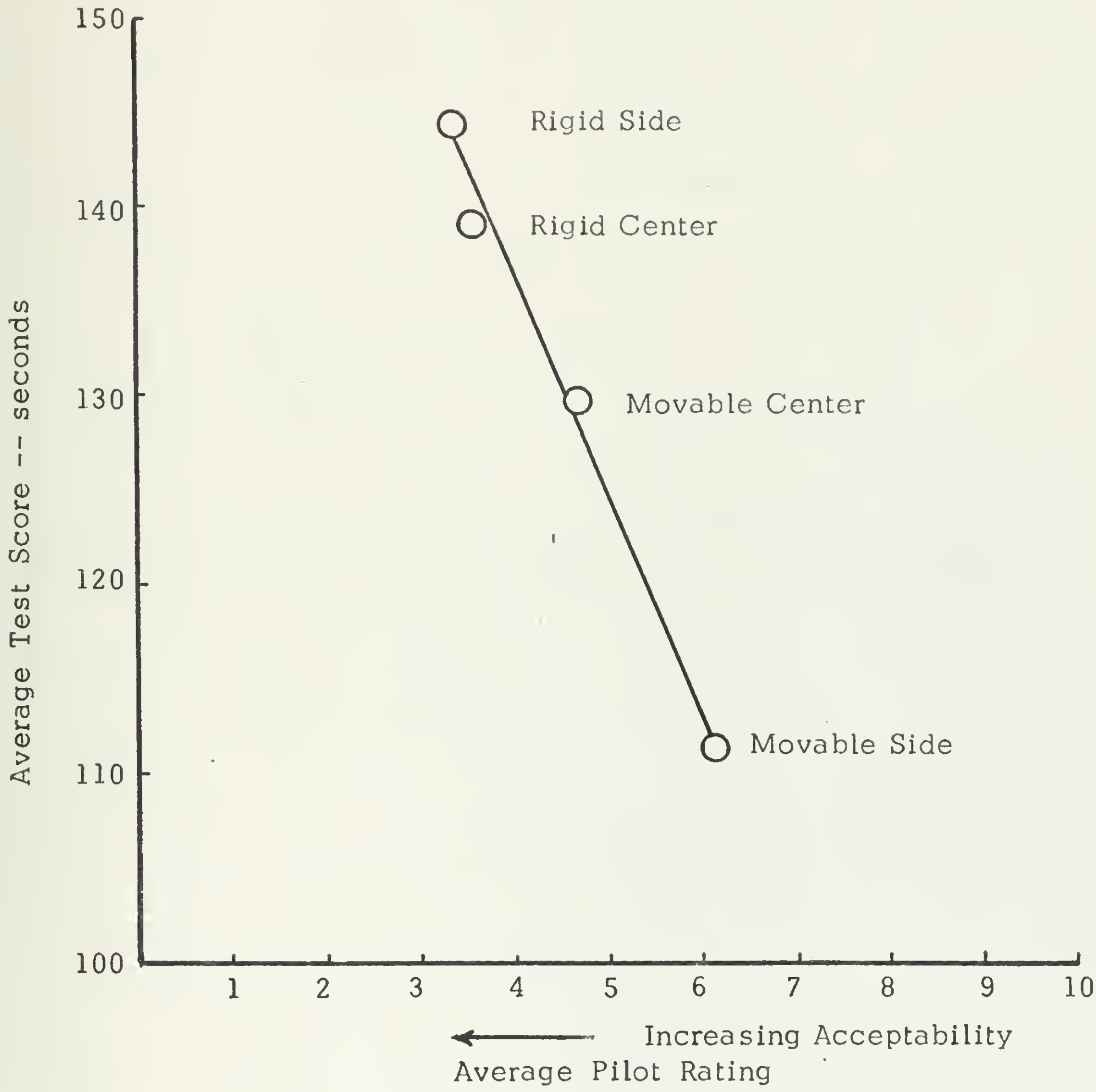

Figure 15. Correlation of Pilot Opinion to Performance

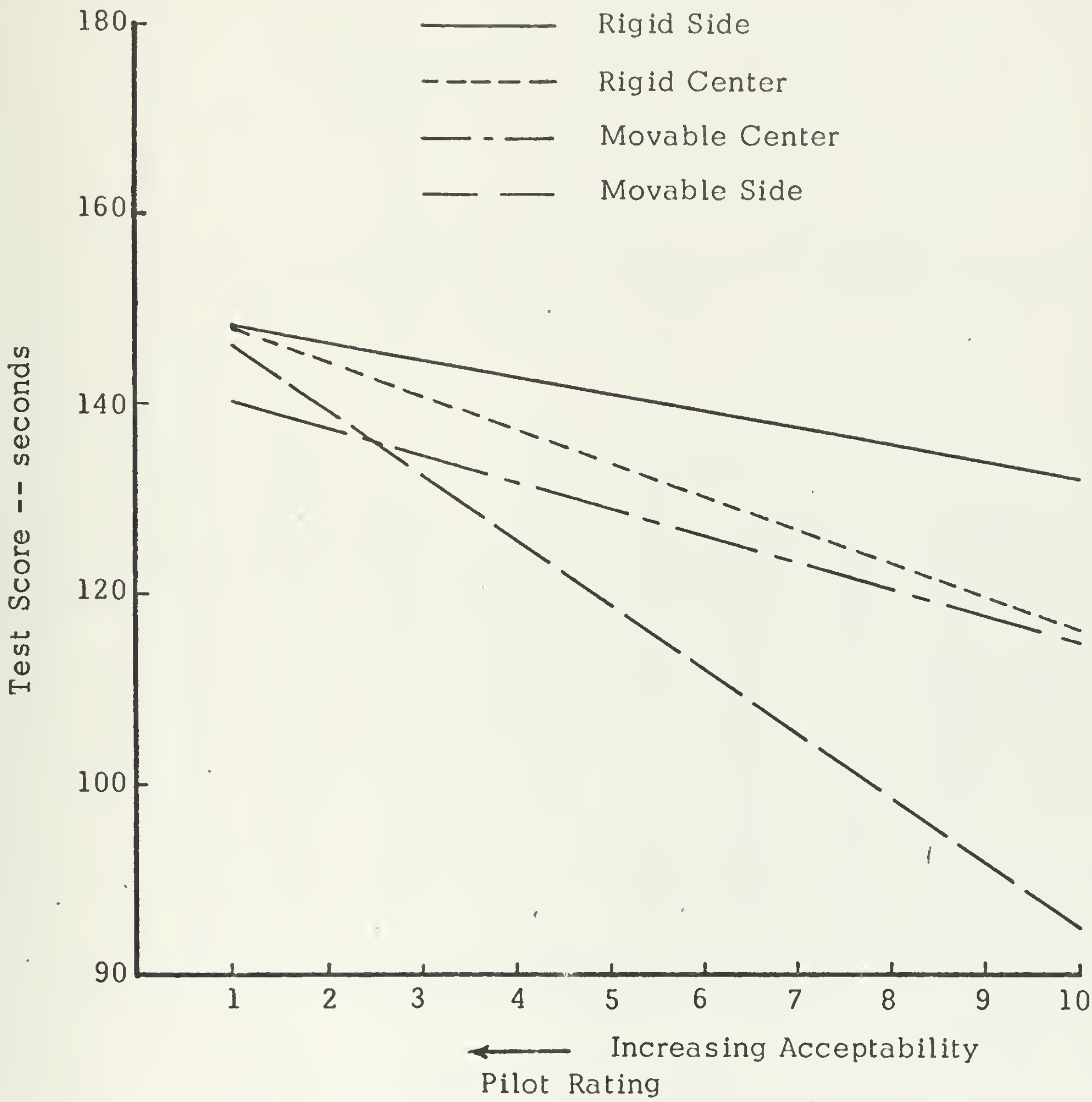

Figure 16. Score-to-Rating Regression Analysis

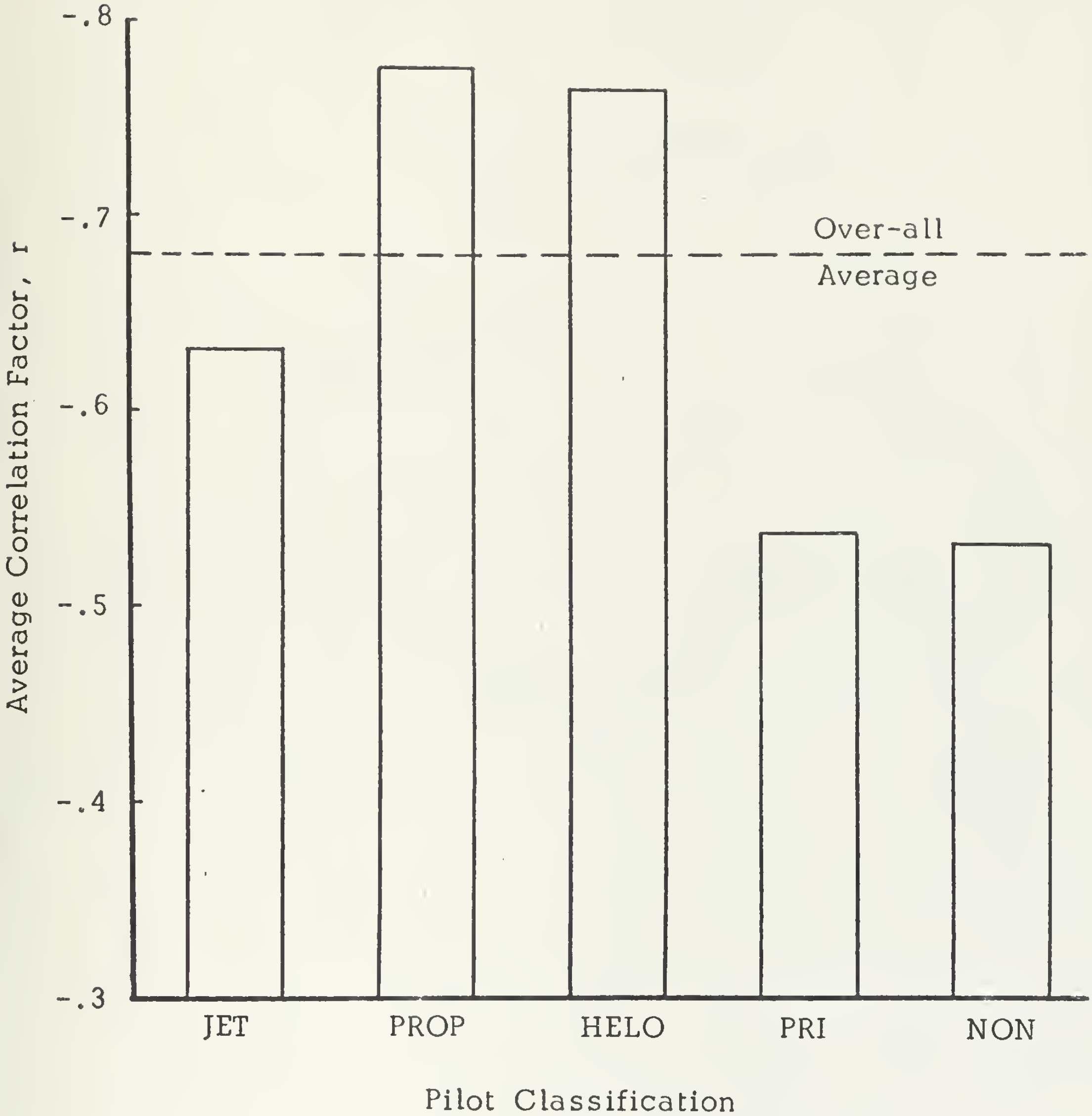

Figure 17. Average Correlations of Scores to Opinions

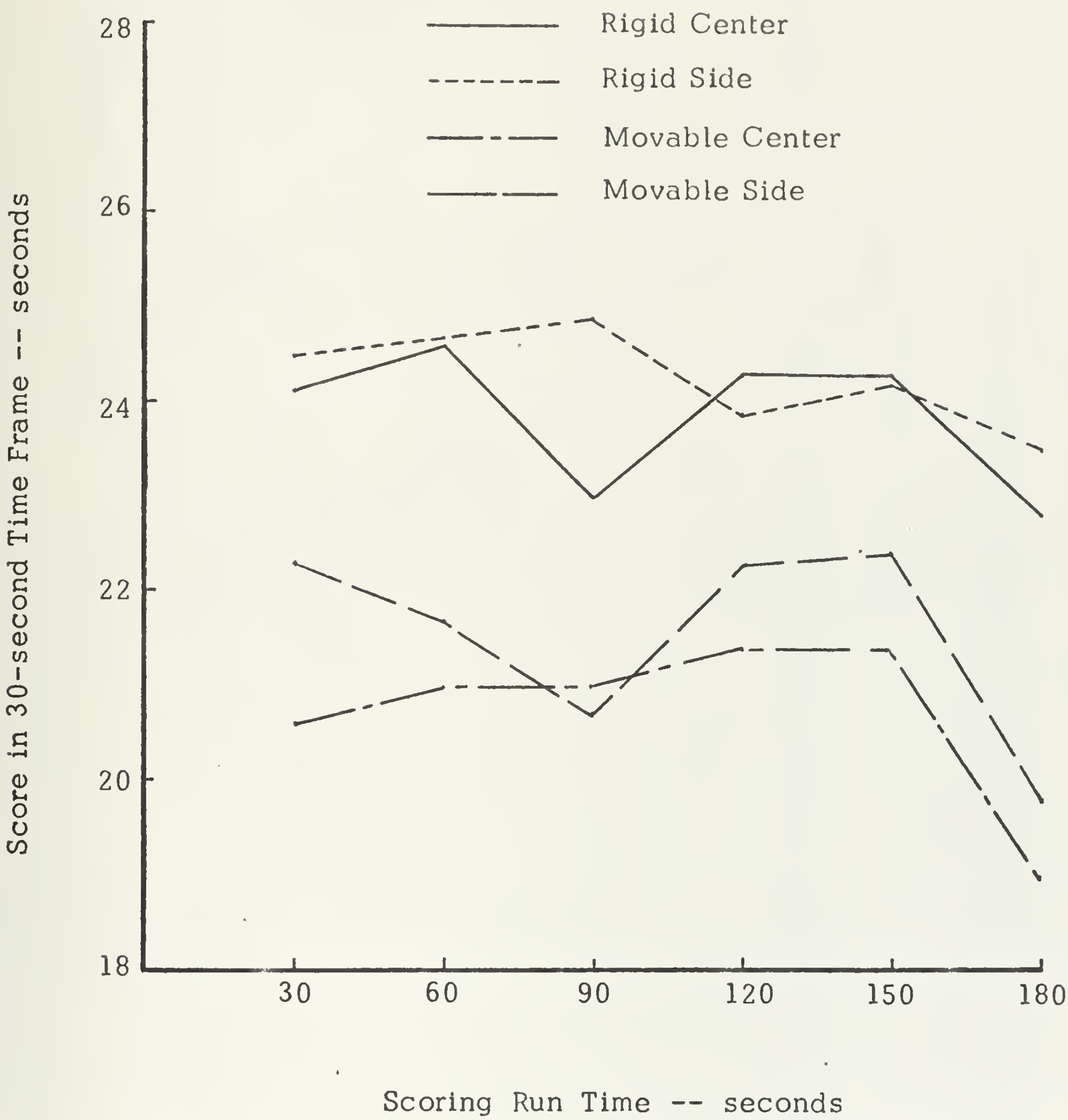

Figure 18. Average Pilot Scoring Pace Throughout Test Run

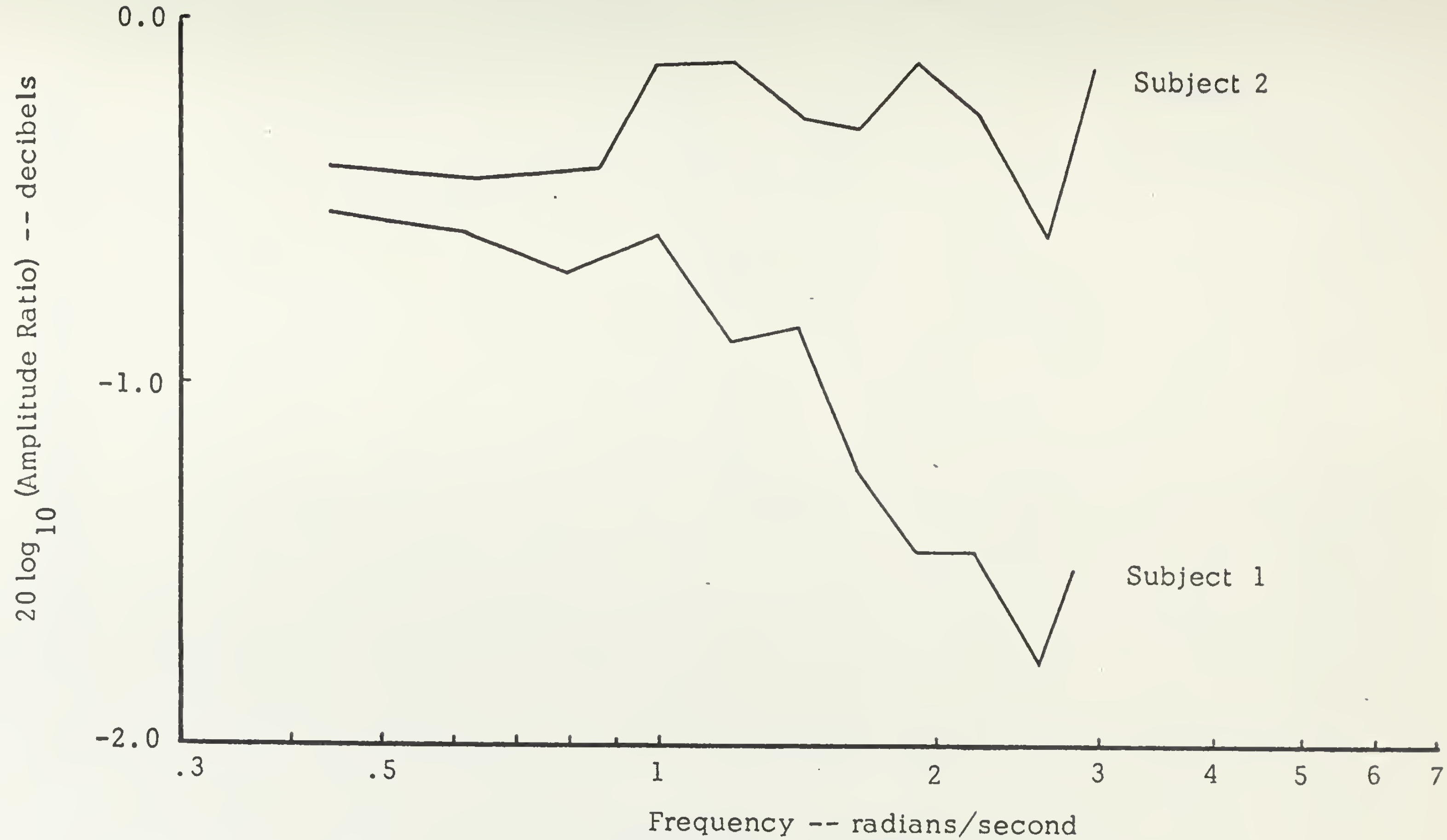

Figure 19. Pilot Frequency Response With Rigid Side-Arm Stick

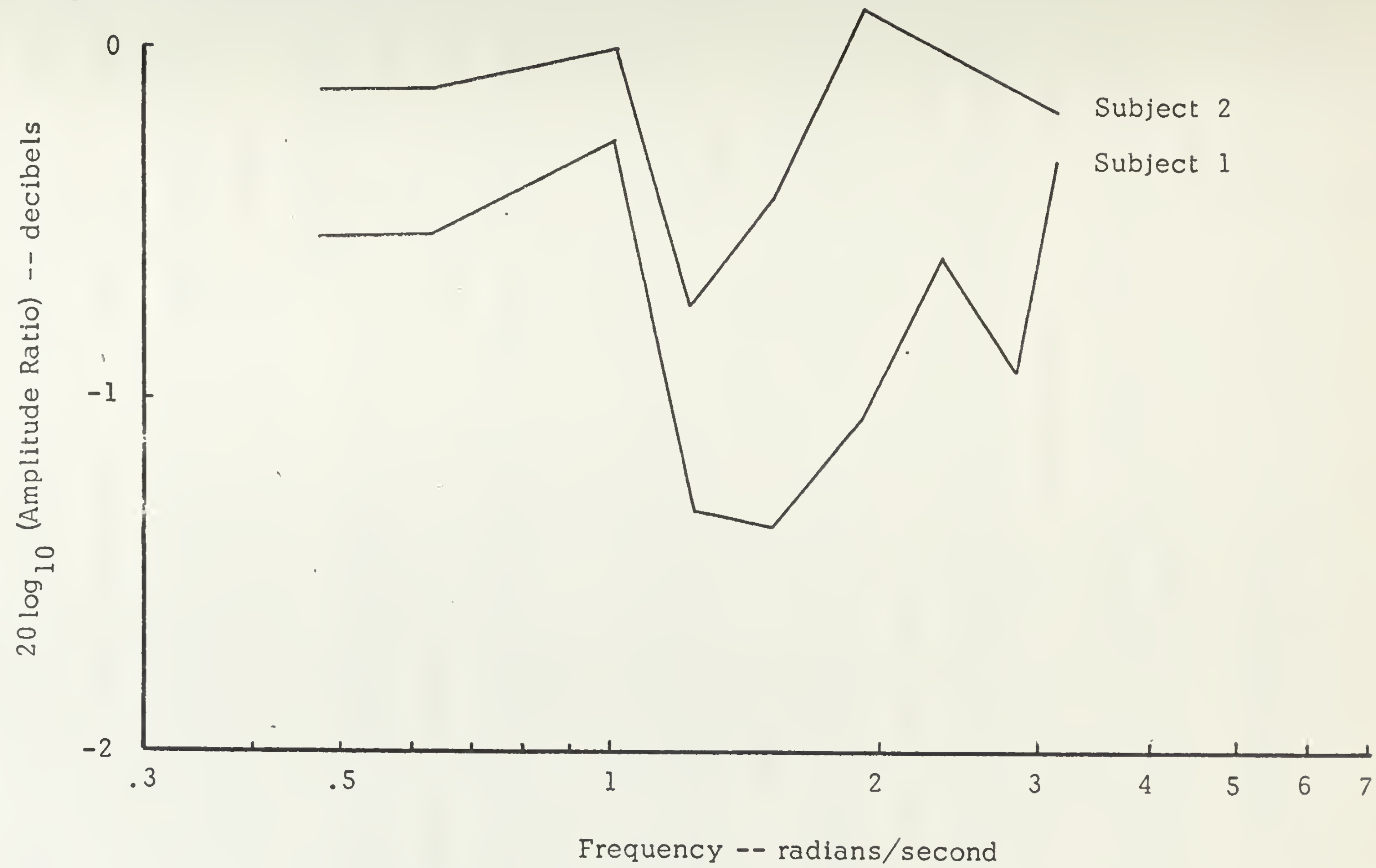

Figure 20. Pilot Frequency Response With Movable Center Stick

VII. DISCUSSIONS AND CONCLUSIONS

The purpose of this investigation was to determine the acceptability to operational military pilots of a rigid cockpit control system and to evaluate their performance using the force-only controls. Within the restricting framework of the test limitations mentioned in the previous section, this has effectively been accomplished. Results were obtained from fifty-five flying and non-flying test subjects operating both movable and rigid controllers in a compensatory tracking task.

To draw specific and meaningful conclusions from the data collected, it is necessary to thoroughly analyze the test subject group in order to determine applicability of the results. At the same time, the particular measurement standards and procedures must be reviewed to insure validity of the test. Finally, in a study involving human opinions, the possible sources of error induced by the subjects and inherent in the test itself must be examined.

The test subject group consisted of Navy and Marine aviators, Naval Flight Officers, private pilots, and non-pilots. The pilots tested were on a proficiency flying status and thus may not have been quite as sharp as their active fleet counterparts. The non-pilot group was highly representative of the personnel who enter Naval flight training (future pilots). A significant number of each pilot classification -- jet, propeller, helicopter, private, and non-pilot --was tested to form a sound base for significant conclusions. The exception was the private pilot class who

showed basically erratic performance and ratings, possibly due to the duration of time since many of them had flown. In general, however, the inexperienced subjects were tested to compare their performance with that of pilots -- their opinions were of lesser importance in the test. The wide variety of aircraft in the pilots' background experience represented the majority of operational aircraft in the fleet today.

The measurement procedures in this investigation were relatively conventional and test validity was protected. The signal error in a compensatory tracking task is a common measure of pilot performance and is a fairly standard procedure. The revised rating scale, allowing the opportunity for finer discriminations, was devised especially for the test. Its success is evidenced by the relatively uniform interpretations it received by the various pilot classifications.

Numerous precise measurements were conducted to eliminate errors induced by the human test subjects and test apparatus. The extensive correlation analysis effectively ruled out pilot bias in most test subjects. It demonstrated that the small amount of bias found tended to cancel itself out; i.e., some pilots preferred the movable system and scored high with the rigid, while others preferred the rigid and scored well with the movable controls. Alternating the testing order of the sticks virtually eliminated pilot learning during the course of the test. Even so, the learning value was a very small number. Most of the pilots experienced fatigue during the final 30 seconds of a run; however, this only introduced a difference of 2-3 seconds in test score. The fatigue

was slightly greater with the movable controls -- another indication of their difficulty, in addition to pilot scores and ratings. No problem was experienced with pilot adaptation to a particular control stick. The tape segment allotted for practice allowed time for a complete adaptation. The error due to a possible change in pip deflection was also negligible, since the relative differences of scores and ratings for each stick remained essentially constant. Thus various safeguards and checks greatly minimized these various possible sources of error in the data.

In general the pilots performed better with the rigid control sticks and preferred them over the movable systems. The rigid side-arm controller was the consensus favorite in both performance and preference. The movable side-arm stick was uniformly disliked and its performance was inferior. The movable deck-mounted stick was only slightly less preferred by the pilots than the rigid systems -- the differences in scores and ratings were not large; whereas the less experienced private and non-pilot group displayed a rather marked preference of rigid over movable controllers with the coincident large difference in performance with each system. These results suggest that a rigid controller is certainly feasible for either a primary control, back-up control, or precision tracker in an aircraft with fly-by-wire capability. It can also be concluded that it would not be economically feasible to replace present movable controls with force-only sticks, since the difference in performance and present-pilot rating is not large. Therefore on the basis of the preliminary results of

this test, the rigid control systems appear feasible for future primary control systems or present secondary tracking functions.

This acceptability and feasibility of the rigid sticks must be examined in light of the test limitations. The foremost consideration in a simulator study is the degree of realism of the simulation. Although many of the pilots expressed concern over this matter, several indications supported an assumption of "airplane-like" simulation: 1) As would be expected, the jet pilots scored higher than all other groups using the conventional movable center stick, 2) The less experienced private and non-pilots had a greater divergence of scores between the movable and rigid systems, and 3) Individual pilot correlations were higher than those of private and non-pilots, as would be expected of men with greater flying experience.

The major simulation limitations deal with low stick force gradients, lack of vibration (as is found in aircraft), and omission of acceleration effects on performance and opinion. This report should not be considered an indictment of a movable side-arm controller. The unrestrained nature of this stick badly hampered its ability to compete with the other three sticks. Vibration effects were not included, and most reports say it detracts from rigid control effectiveness. Acceleration could not be included in a simulator study, of course; there is a strong possibility that a rigid control system is superior under high g conditions, due to the difficulty of gross arm motion.

Thus all of these limitations could seriously affect the pilot performance and acceptance of rigid control systems reported in this study. The results here essentially indicate a preliminary feasibility, with a strong requirement for future investigation and flight testing.

VIII. RECOMMENDATIONS

Viewing the results of this investigation, several specific recommendations concerning future compensatory tracking tests and future work with rigid control systems come to mind.

A. CONTROLLER EVALUATION TESTS

When evaluating more than one control stick using an identical signal input for each one, as was the case in this investigation, a great deal of time could be saved by having the four identical signals on one long tape rather than having one signal which requires rewinding. Since the subjects encountered little or no adaptation troubles, the rest periods and the practice runs could be shortened somewhat. These measures would tend to shorten the test time for an individual subject and thus decrease his fatigue.

Future control stick evaluation studies should also allow the pilots to rate other qualities of the controller such as sensitivity, location, feel, deflection, force levels, naturalness of control, good and bad features, and coordination of the control modes. This would overcome possible limitations of the 10-point rating scale in this test. For finer discriminations between two nearly identical sticks (such as rigid center vs. rigid side-arm) the pilots could also be allowed to give fractional ratings such as 3.5 or 4.6.

B. RIGID CONTROL SYSTEMS

Before a precise judgement can be made as to the acceptability and applicability of a rigid controller, several problem areas should be investigated. Chief among these is the matter of stick force gradients. A man-machine optimization testing program is required to compare the rigid and movable control systems through a range of stick forces. The optimum force and motion combination for a movable stick should then be compared to the optimum stick force for a rigid system. Only then can the applicability of a rigid system be determined -- both on the basis of performance and pilot opinion. A system has already been designed which allows the test subject to alter his own force levels in the cockpit simulator.

A second major area to be investigated is the effects of aircraft vibration on a pilot's performance and opinion. A vibration testing program in a simulator should include a wide range of exciting frequencies to cover those found in the numerous types of military fixed-wing and helicopter aircraft. The program should also determine the effects of introducing the vibration excitation in several directions -- normal to the lateral, longitudinal and vertical axes.

To further approach a realistic simulation, the control sticks could be provided with a break-out force as found in actual aircraft. A trim switch could be included on the sticks to ascertain the problem this might produce with the rigid controllers. Finally, as a further

attempt to simulate the pilots' working condition in the cockpit, the test subject could be occupied with other duties during a run to evaluate the effects of distractions on his ability to use the various sticks.

A variation of in-flight conditions such as different turbulence levels might have a large effect on pilot acceptance of a rigid stick. These different levels could be produced in the simulator by altering the speed, magnitude, and smoothness of the pip deflection on the oscilloscope display.

Various flight modes should be studied to more accurately depict the applicability of the rigid control system. An example would be to find pilot performance and opinion using the four control sticks in a simulated landing approach.

If investigations such as those mentioned still indicate the feasibility of a rigid cockpit control system in operational aircraft, a flight testing program should be initiated for a definite and conclusive answer to the question.

APPENDIX A

LIST OF EQUIPMENT UTILIZED

1. Two Channel Electric Recorder

   Brush Electronics

2. Low Frequency Function Generator, Model 202A

   Hewlett-Packard

3. Models 120A and 130A Oscilloscope

   Hewlett-Packard

4. Universal Eput and Timer

   Berkeley Division Beckman's

5. Pace TR-10 Analog Computer, Model 7350

   Electronic Associates, Inc.

6. Lab-Chron 115-volt 60 cps Timer

   Laboratory Industries, Inc.

7. Power Supply (two) Model 3569 15/30 v.

   System Research Corporation

APPENDIX B

PILOT FLIGHT EXPERIENCE DATA

SUBJECT	AGE	SEJ	MEJ	SEP	MEP	HELO	PRI	CLASSIFICATION
1	21	---	---	---	---	----	---	NON
2	27	850	---	300	---	----	---	JET
3	22	---	---	---	---	----	---	NON
4	22	---	---	---	---	----	---	NON
5	35	1500	100	1200	800	15	10	JET/PROP
6	47	---	---	700	6300	----	---	PROP
7	30	---	---	---	---	----	---	NON
8	30	---	---	6--	2200	----	---	PROP
9	29	---	---	---	2500	----	---	PROP
10	30	---	---	400	800	----	---	PROP
11	28	---	---	400	---	700	---	HELO
12	32	---	---	1000	750	1000	---	PROP/HELO
13	28	1250	---	30	80	----	---	JET
14	30	11	---	200	---	1100	---	HELO
15	29	---	---	---	2400	----	---	PROP
16	28	300	1100	30	8	----	---	JET
17	29	---	---	100	2300	----	---	PROP
18	28	---	---	300	---	2100	---	HELO
19	29	2500	---	200	---	----	---	JET
20	28	1400	---	60	10	----	10	JET
21	27	1000	---	300	---	----	---	JET
22	26	---	---	140	---	1800	---	HELO
23	30	---	---	---	---	----	---	NON
24	26	875	---	30	---	----	---	JET
25	23	---	---	---	---	----	---	NON

SUBJECT	AGE	SEJ	MEJ	SEP	MEP	HELO	PRI	CLASSIFICATION
26	28	200	1250	100	50	----	50	JET
27	28	2700	---	150	---	----	---	JET
28	27	---	---	150.	---	1800	---	HELO
29	29	700	000	1300	---	----	---	JET/PROP
30	28	---	---	---	2500	----	---	HELO
31	29	2400	5	300	---	----	---	JET
32	28	---	---	200	---	1700	---	HELO
33	29	---	1200	300	---	----	---	JET
34	23	---	---	---	---	----	45	PRI
35	24	---	---	---	---	----	48	PRI
36	34	1200	2500	400	---	----	---	JET
37	23	---	---	---	---	----	---	NON
38	29	---	1400	250	---	----	---	JET
39	27	1400	---	250	---	----	---	JET
40	30	---	---	250	---	1100	---	HELO
41	22	---	---	---	---	----	60	PRI
42	24	---	---	---	---	----	160	PRI
43	27	---	1200	50	---	10	---	JET
44	28	---	---	250	1400	----	---	PROP
45	29	---	---	---	---	----	900	PRI
46	28	---	---	100	2000	----	---	PROP
47	22	---	---	---	---	----	60	PRI
48	28	---	---	---	---	----	80	PRI
49	31	---	---	---	---	----	---	NON
50	23	---	---	---	---	----	---	NON

SUBJECT	AGE	SEJ	MEJ	SEP	MEP	HELO	PRI	CLASSIFICATION
51	35	---	---	300	4000	----	50	PROP
52	24	---	---	---	---	----	48	PRI
53	31	2000	---	50	50	----	---	JET
54	28	350	200	350	1400	----	---	PROP
55	27	---	---	100	30	770	---	HELO

SEJ -- Single-Engine Jet Hours

MEJ -- Multi-Engine Jet Hours

SEP -- Single-Engine Prop Hours

MEP -- Multi-Engine Prop Hours

HELO -- Helicopter Hours

PRI -- Private Pilot Hours

APPENDIX C

PILOT SCORING AND RATING DATA

SUBJECT NUMBER	TEST SCORE R.C.	TEST SCORE R.S.	TEST SCORE M.C.	TEST SCORE M.S.	PILOT RATING R.C.	PILOT RATING R.S.	PILOT RATING M.C.	PILOT RATING M.S.	TESTING ORDER
1	159	174	89	82	3	2	5	8	CDAB
2	161	173	106	122	4	3	6	5	CDAB
3	132	156	160	110	9	7	5	8	ABCD
4	152	171	152	114	3	2	3	9	CDAB
5	107	135	146	81	3	4	7	9	ABCD
6	137	82	138	80	3	6	3	8	ABCD
7	152	171	126	89	4	7	3	10	CDAB
8	130	125	148	90	4	4	5	8	ABCD
9	152	130	145	105	5	3	3	7	ABCD
10	142	148	131	101	3	2	7	8	ABCD
11	125	131	106	87	3	3	5	4	CDAB
12	120	116	120	97	3	4	6	7	ABCD
13	139	132	137	132	7	4	5	4	CDAB
14	125	170	118	102	3	3	5	7	ABCD
15	158	162	138	93	2	4	3	6	CDAB
16	154	161	159	83	7	4	3	8	ABCD
17	110	143	134	90	5	3	4	9	CDAB
18	137	140	134	87	3	2	4	5	ABCD
19	124	137	117	91	3	2	4	5	CDAB
20	96	109	131	87	6	3	5	8	ABCD
21	152	152	139	93	2	2	4	7	CDAB
22	93	139	135	128	8	7	8	6	ABCD
23	151	166	148	153	2	2	4	2	CDAB

SUBJECT	TEST SCORE				PILOT RATING				TESTING
NUMBER	R.C.	R.S.	M.C.	M.S.	R.C.	R.S.	M.C.	M.S.	ORDER
24	168	175	165	102	3	3	7	9	CDAB
25	124	132	119	80	2	2	5	10	ABCD
26	146	140	159	88	3	4	5	6	CDAB
27	110	109	98	87	3	2	4	5	ABCD
28	122	126	106	89	3	2	7	8	CDAB
29	142	145	120	94	3	2	5	8	ABCD
30	132	142	131	80	4	3	3	10	CDAB
31	126	145	118	99	5	2	7	8	ABCD
32	141	144	131	110	3	2	5	6	CDAB
33	131	138	128	118	3	2	7	8	ABCD
34	166	169	125	153	3	2	5	5	CDAB
35	152	163	159	165	4	4	6	6	ABCD
36	162	151	126	127	4	7	3	3	CDAB
37	162	169	161	168	2	2	4	3	ABCD
38	155	142	151	124	3	4	2	7	ABCD
39	140	138	143	129	3	3	4	5	CDAB
40	138	131	142	136	2	2	2	3	ABCD
41	176	176	168	159	2	2	3	5	ABCD
42	148	143	134	134	5	7	2	2	ABCD
43	153	152	104	118	2	2	2	2	CDAB
44	137	142	123	121	3	3	4	5	ABCD
45	140	139	116	130	2	3	5	4	CDAB
46	135	125	88	110	3	4	4	4	CDAB
47	147	143	134	130	2	2	3	5	ABCD
48	139	137	114	112	1	2	6	6	CDAB
49	134	146	100	105	2	4	7	5	ABCD
50	148	154	134	128	3	5	5	6	ABCD

SUBJECT	TEST SCORE				PILOT RATING				TESTING
NUMBER	R.C.	R.S.	M.C.	M.S.	R.C.	R.S.	M.C.	M.S.	ORDER
51	139	160	109	124	4	4	8	7	ABCD
52	128	146	130	136	7	4	3	7	ABCD
53	150	160	130	126	5	4	7	3	CDAB
54	108	83	91	107	5	5	6	4	ABCD
55	143	155	133	134	3	3	4	4	CDAB

A -- Rigid Center Stick (R.C.)

B -- Rigid Side Stick (R.S.)

C -- Movable Center Stick (M.C.)

D -- Movable Side Stick (M.S.)

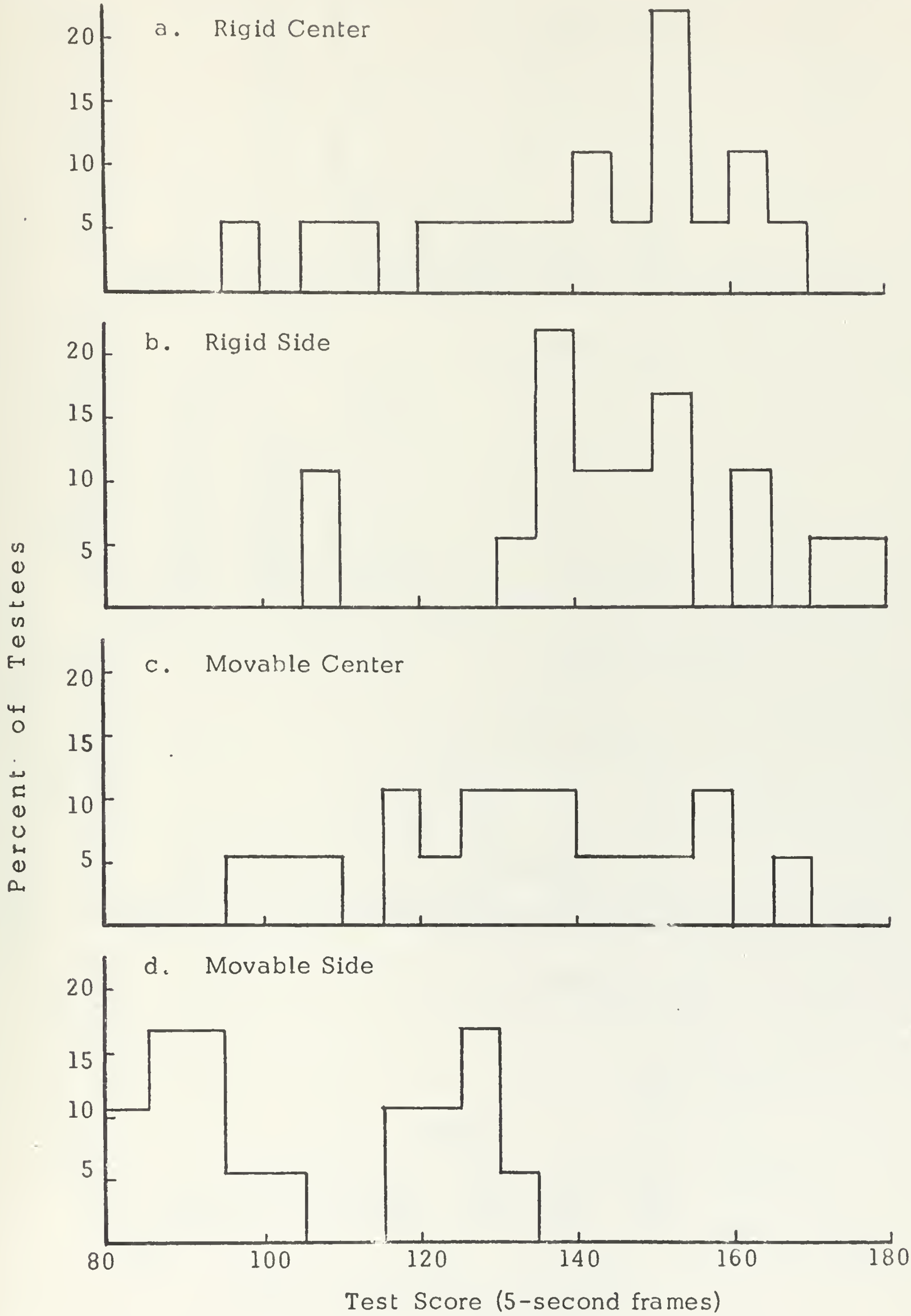

Figure D-1. Distribution of Test Scores -- Jet Pilots

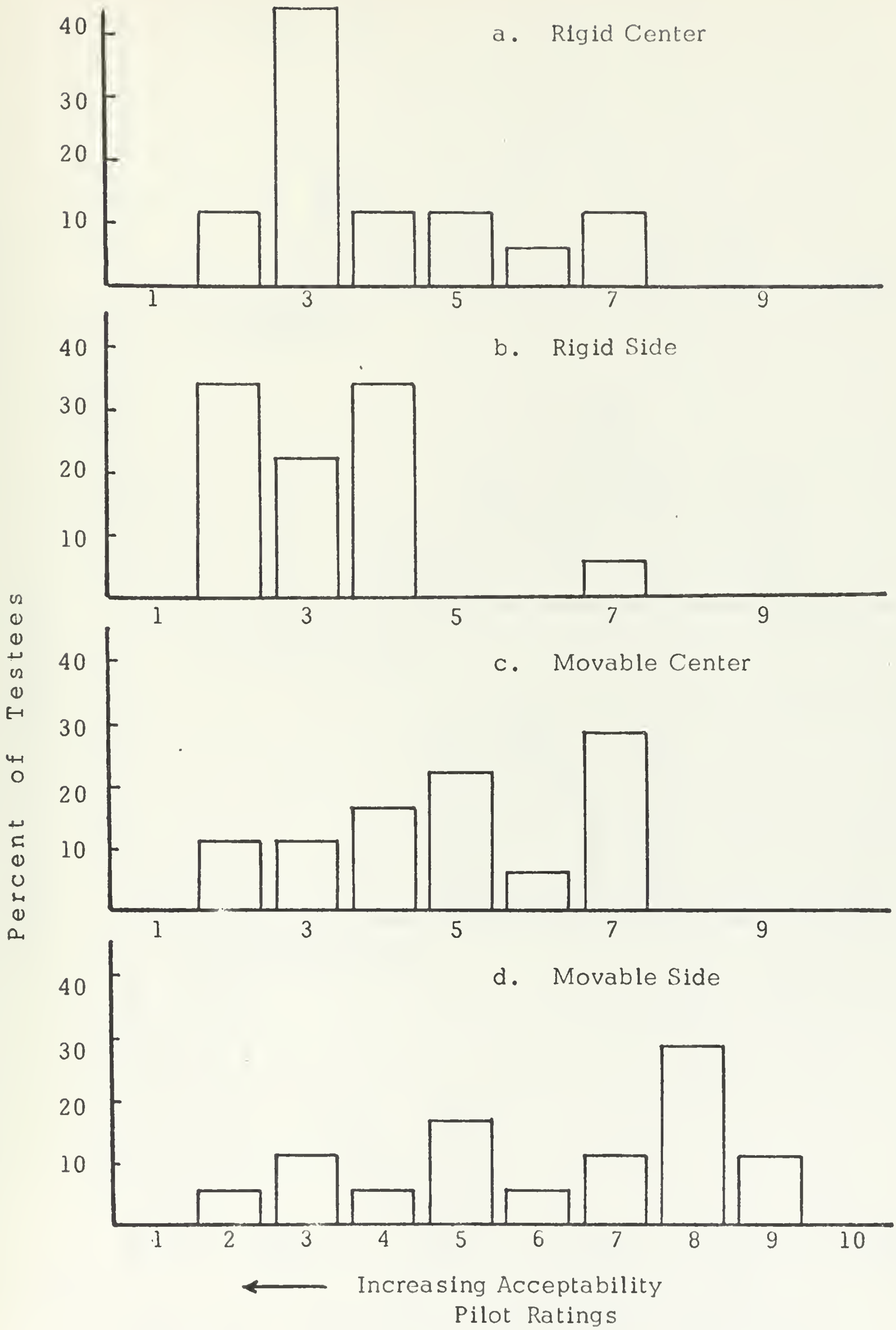

Figure D-2. Distribution of Opinions -- Jet Pilots

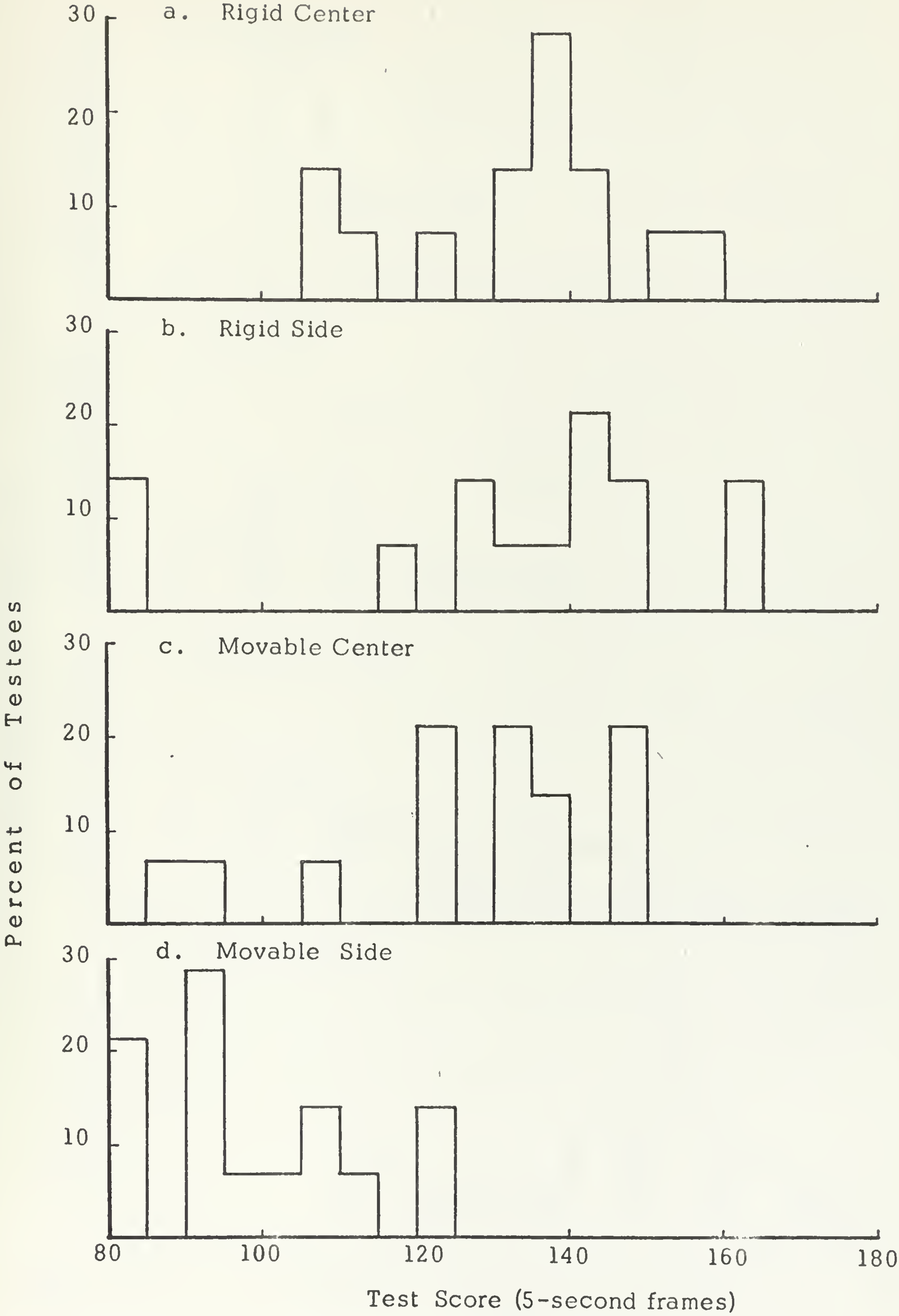

Figure D-3. Distribution of Test Scores -- Prop Pilots

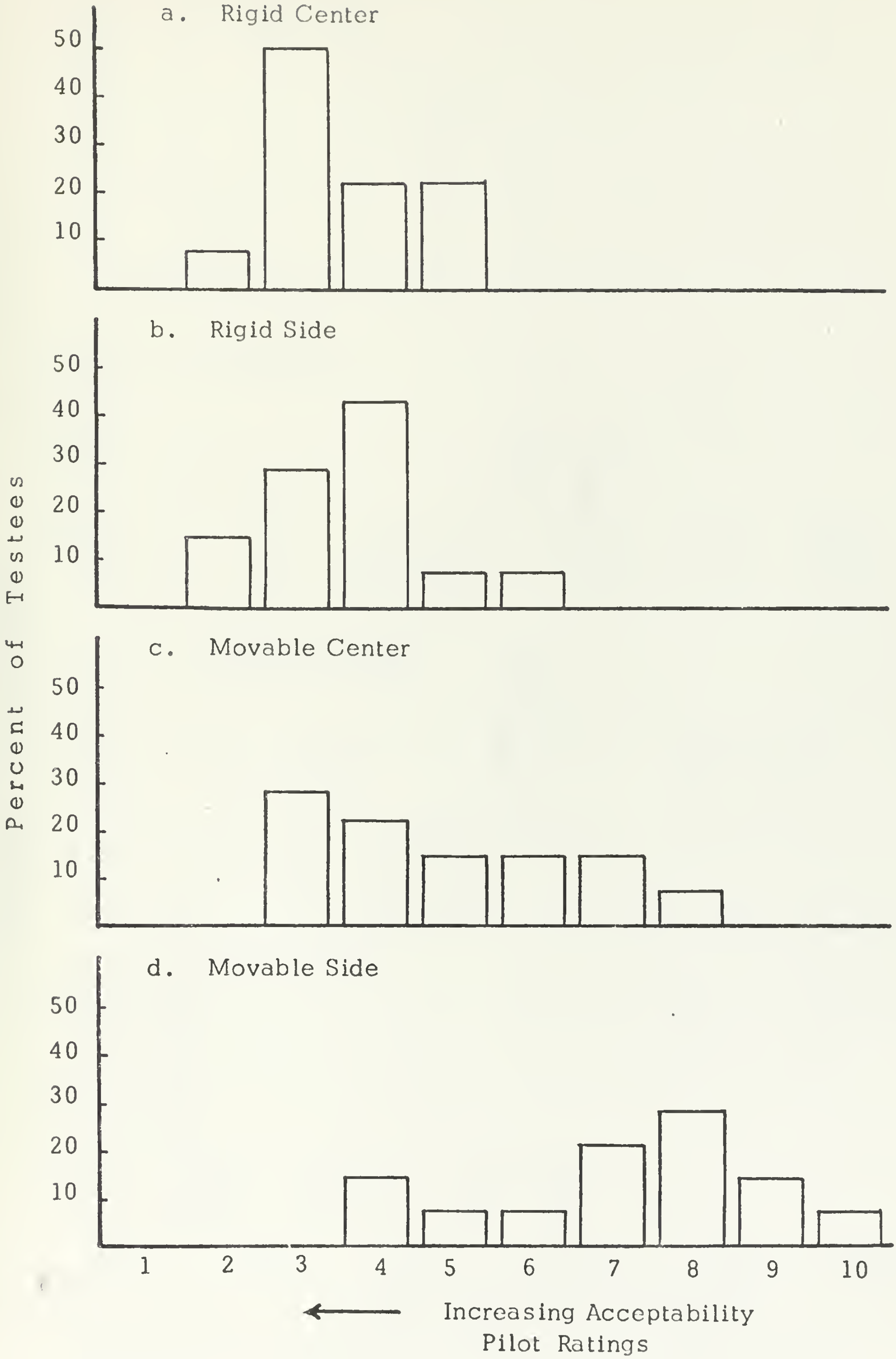

Figure D-4. Distribution of Opinions -- Prop Pilots

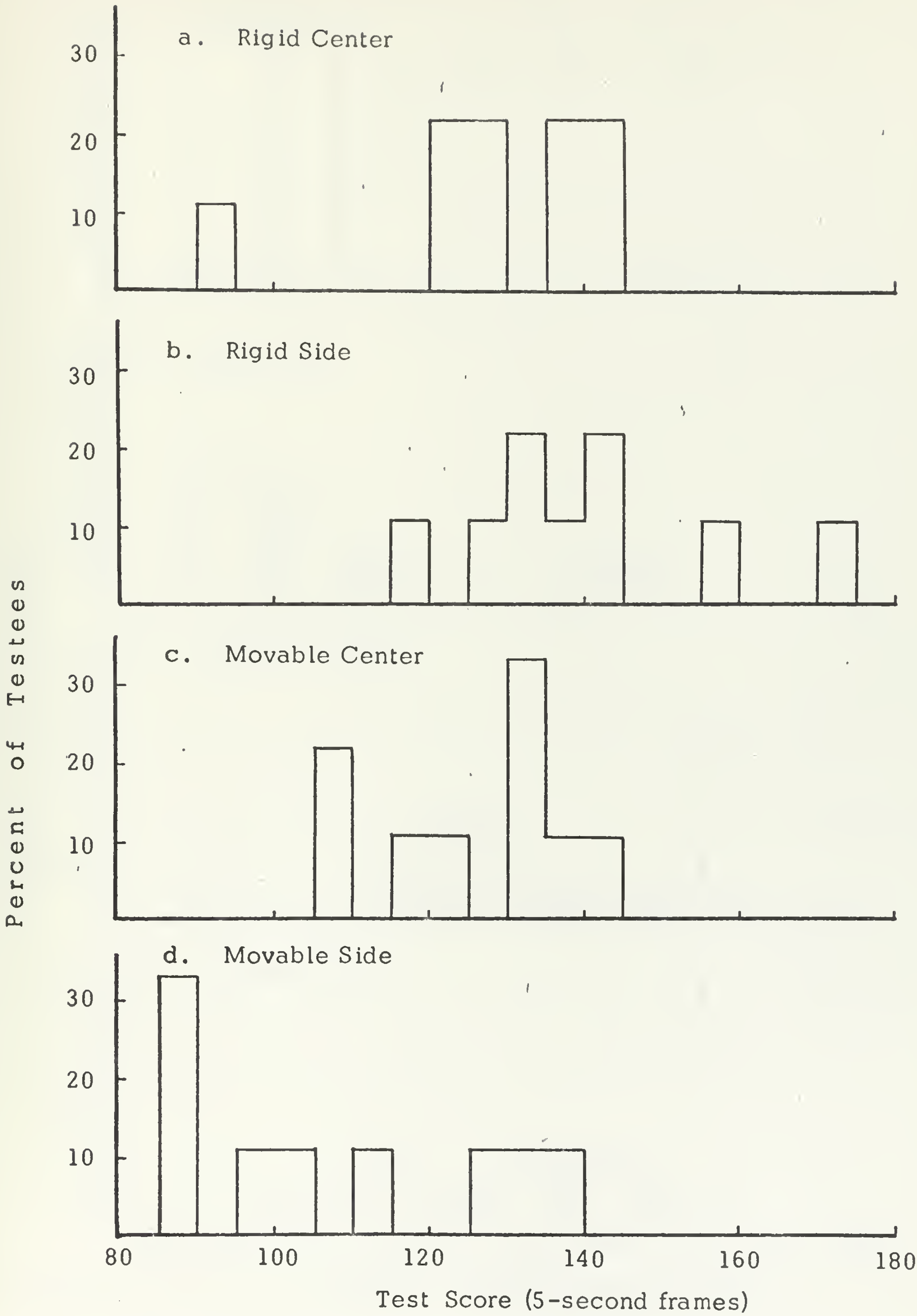

Figure D-5. Distribution of Test Scores -- Helo Pilots

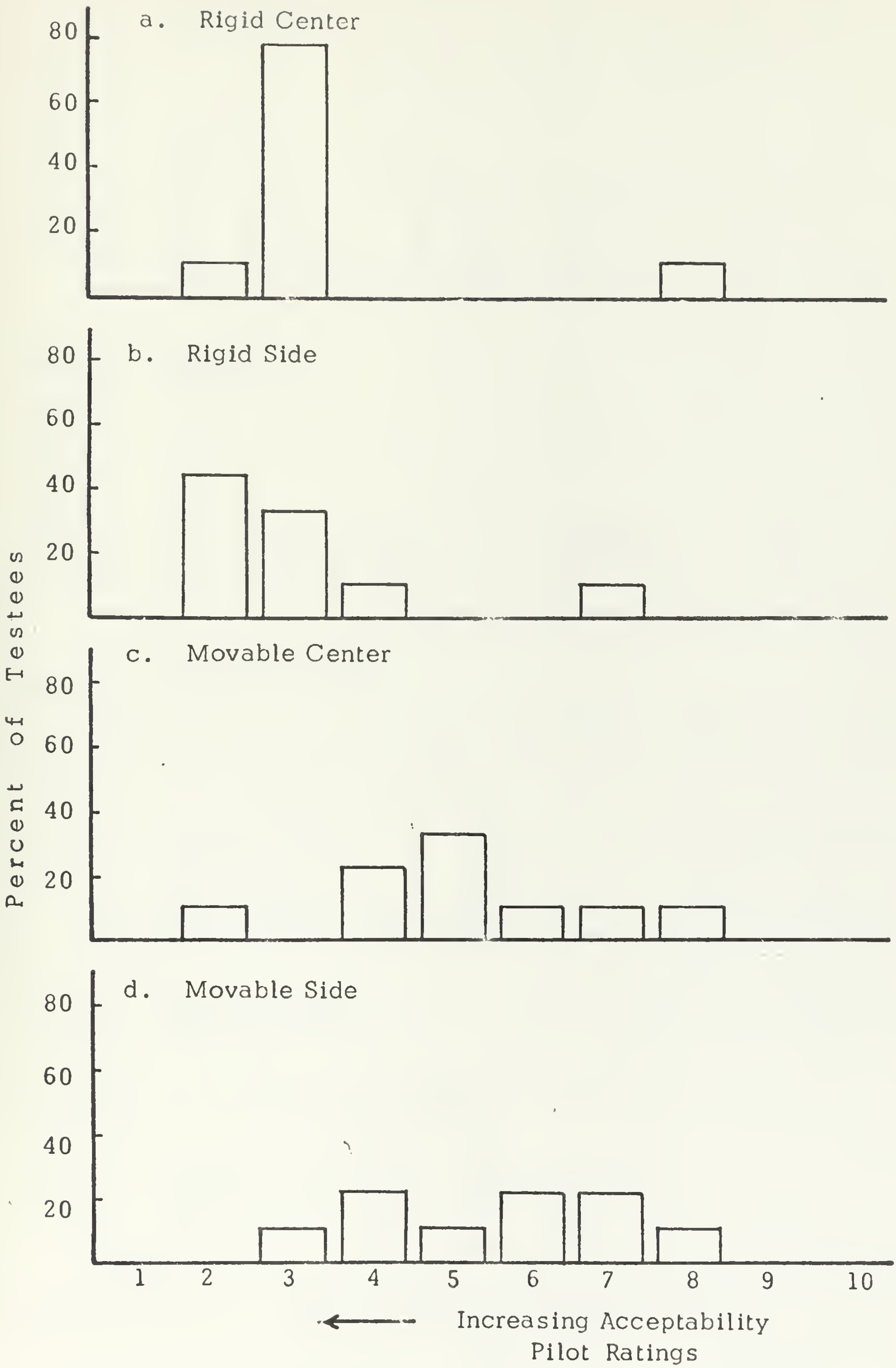

Figure D-6. Distribution of Opinions -- Helo Pilots

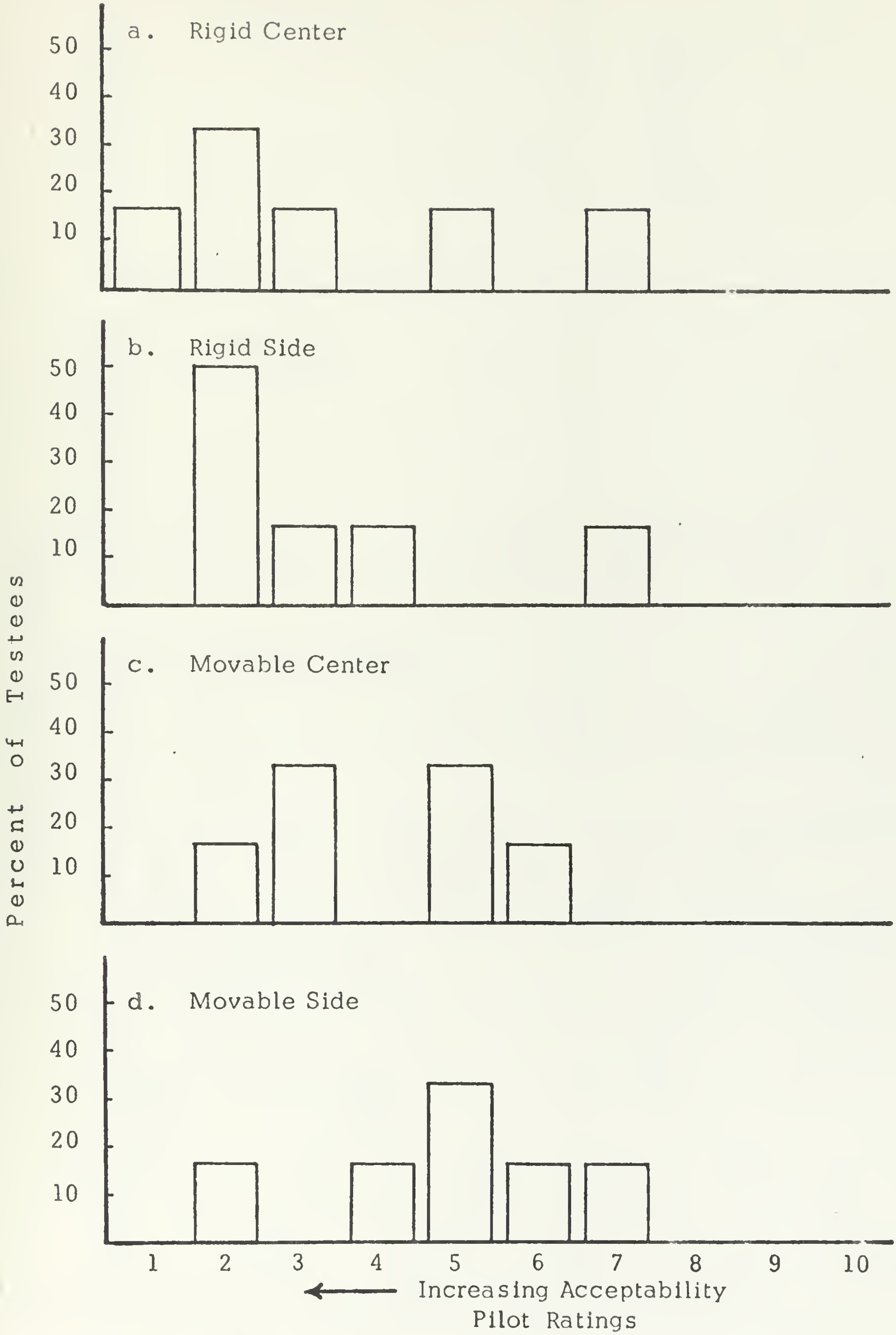

Figure D-8. Distribution of Opinions -- Private Pilots

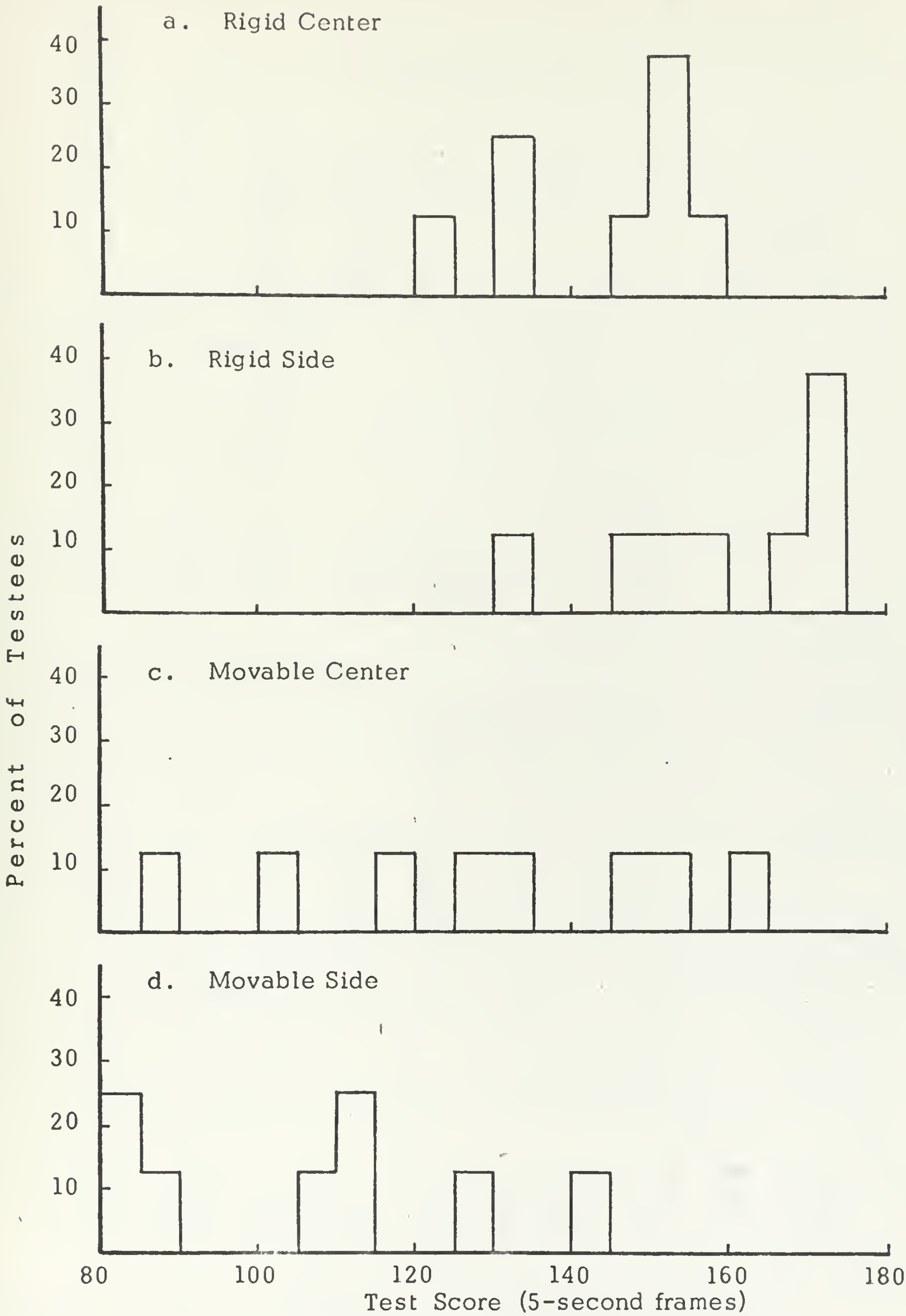

Figure D-9. Distribution of Test Scores -- Non-Pilots

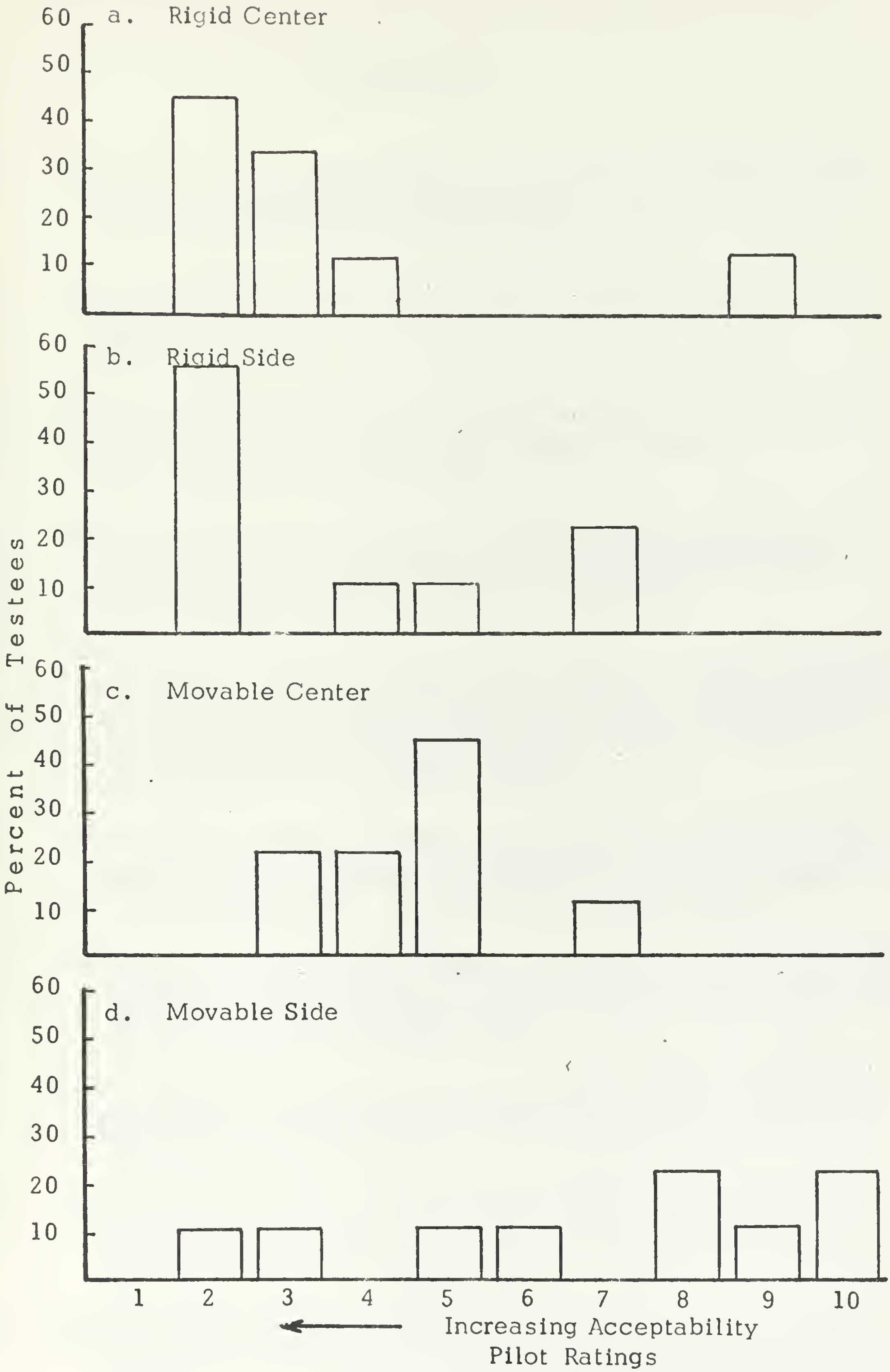

Figure D-10. Distribution of Opinions -- Non-Pilots

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13. ABSTRACT

A simulator facility employing a two-axis compensatory tracking task with a random-appearing signal was used to evaluate the performance of fifty-five pilot and non-pilot test subjects using four separate control sticks -- two movable and two rigid. Pilot acceptance of the rigid cockpit controllers was determined by comparing individual pilot ratings of the sticks. In general, in both performance and opinion, the rigid systems were found to be superior to their movable counterparts. Steps were taken to avoid errors due to pilot bias, learning, adaptation, or fatigue. The results obtained are subject to several test limitations, including the low stick-force levels used, neglect of aircraft vibration effects, and the realism of the simulation.

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